A Tectonic Model for the Spatial Occurrence of Porphyry Copper and Polymetallic Vein Deposits—Applications to Central Europe

Scientific Investigations Report 2005–5272

U.S. Department of the Interior
U.S. Geological Survey

A Tectonic Model for the Spatial Occurrence of Porphyry Copper and Polymetallic Vein Deposits—Applications to Central Europe

By Lawrence J. Drew

Scientific Investigations Report 2005–5272

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Dirk Kempthorne, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

On the cover: View of the Assarel porphyry copper deposit, the largest open-pit mine in Bulgaria. Production is more than 10 million metric tons per year of ore, from which 180,000 metric tons of copper concentrate is extracted (0.45 percent copper, 2.5 grams per metric ton gold). The mine is located in the Panagyurishte area, which is within the central Srednogorie region of central Bulgaria. The snow-covered Stara Planina Mountains in the background are seen 40 kilometers to the south. This area is famous for the discovery in the 1950s of a fabulous gold treasure dating to 2,500 B.C., and the region has a rich mining history since before Thracian time. The mine is located near the headwaters of the Luda Yana River, which flows into the Maritsa River, which then flows southward across Bulgaria and Greece, into the Aegean Sea. Photograph by Lawrence J. Drew.

Suggested citation:
Drew, L.J., A tectonic model for the spatial occurrence of porphyry copper and polymetallic vein deposits—Applications to central Europe: U.S. Geological Survey Scientific Investigations Report 2005–5272, 36 p.

Library of Congress Cataloging-in-Publication Data

Drew, Lawrence J.
A tectonic model for the spatial occurrence of porphyry copper and polymetallic vein deposits : applications to central Europe / by Lawrence J. Drew.
p. cm. – (Scientific investigations report ; 2005-5272)
Includes bibliographical references.
ISBN 1-411-30960-X
1. Porphyry–Europe, Central. 2. Copper–Europe, Central. 3. Sediments (Geology)–Europe, Central.
4. Hydrothermal deposits–Europe, Central. 5. Geology, Stratigraphic–Cretaceous. 6. Geology, Stratigraphic–Miocene. 7. Geology–Europe, Central. I. Title.

QE462.P6D74 2006
553.4’30943–dc22

2006041307

Contents

Figures

Table

Conversion Factors

Multiply	By	To obtain
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
kilogram (kg)	2.205	pound avoirdupois (lb)

A Tectonic Model for the Spatial Occurrence of Porphyry Copper and Polymetallic Vein Deposits—Applications to Central Europe

By Lawrence J. Drew

Abstract

A structural-tectonic model, which was developed to assess the occurrence of undiscovered porphyry copper deposits and associated polymetallic vein systems for the Mátra Mountains, Hungary, has been expanded here and applied to other parts of central Europe. The model explains how granitoid stocks are emplaced and hydrothermal fluids flow within local strain features (duplexes) within strike-slip fault systems that develop in continental crust above subducting plates. Areas of extension that lack shear at the corners and along the edges of the fault duplexes are structural traps for the granitoid stocks associated with porphyry copper deposits. By contrast, polymetallic vein deposits are emplaced where shear and extension are prevalent in the interior of the duplexes. This model was applied to the Late Cretaceous-age porphyry copper and polymetallic vein deposits in the Banat-Timok-Srednogorie region of Romania-Serbia-Bulgaria and the middle Miocene-age deposits in Romania and Slovakia. In the first area, porphyry copper deposits are most commonly located at the corners, and occasionally along the edges, of strike-slip fault duplexes, and the few polymetallic vein deposits identified are located at interior sites of the duplexes. In the second area, the model accounts for the preferred sites of porphyry copper and polymetallic vein deposits in the Apuseni Mountains (Romania) and central Slovakian volcanic field (Slovakia).

Introduction

The purpose of this study is to present tectonic data and analyses relevant to the occurrence of porphyry copper and associated polymetallic vein, skarn, and replacement deposits. The primary goal is to develop a tectonic deposit occurrence model useful for assessing the occurrence of undiscovered deposits in the porphyry copper and related family of deposits. The model further quantifies the assessment of the occurrence of undiscovered mineral resources in porphyry and polymetallic vein deposits. A second goal is to provide historical context for this recent research work. Some of the ideas about the relation between structural geology and polymetallic veins were elucidated before 1950. A third goal is to set out instructional ideas for the use of the tectonic occurrence model to assess undiscovered mineral resources.

Many porphyry copper and associated polymetallic vein deposits occur in central Europe. These deposits have been well described, and geologic maps of the area show tectonic and geologic information that was useful for expanding and further testing the tectonic deposit occurrence model. Three areas in central Europe were studied in detail (fig. 1). The first is the Banat-Timok-Srednogorie region in Romania, Serbia, and Bulgaria, where the porphyry copper and associated mineralization is Late Cretaceous to Paleocene in age. The second area is the central Slovakian volcanic field in Slovakia. The third area comprises the Apuseni Mountains in Romania. The mineralization in the latter two areas is middle Miocene in age. To avoid cumbersome repetition, the skarn and replacement deposits that belong to this family are here included under the title "polymetallic vein deposits."

The analytical framework used in this study is based on the tectonics of porphyry-related stock emplacement and the formation of porphyry-style mineralization and associated polymetallic veins, as described by Cox (1986). This framework is expanded into a tectonic deposit occurrence model. The principal elements considered in the model include (1) the association between strike-slip faulting and the emplacement of porphyry stocks (Seraphim and Hollister, 1976; Titley and Beane, 1981); (2) the thermal regimes necessary for development of a mineralized porphyry stockwork (Burnham, 1979; Titley and Beane, 1981; Titley, 1990); and (3) the temporal transition from the deposition of a porphyry stockwork to the formation of polymetallic veins.

Carranza and Hale (2002) introduce a statistical basis for the assessment of porphyry copper deposits using tectonic elements, such as strike-slip faulting. Their conclusions support quantitative mineral resource assessments. The methods used here, by contrast, focus on building the tectonic and geologic reasoning to move from the description of the occurrence of past discoveries to the use of structural and tectonic data to forecast the probable location of undiscovered deposits. This progression from investigation and description to forecasting using a geologic based model, can, hopefully, be achieved through a synthesis of tectonic principles and geologic data. The goal is to move the field of resource assessment from its

Figure 1. Location of three regions (the Banat-Timok-Srednogorie region, the Apuseni Mountains, and the central Slovakian volcanic field) where porphyry copper deposits occur in central Europe. Modified from Borcoş (1994) and Fodor and others (1999).

subjective basis heavily weighted in expert judgment (qualitative) toward a more objective basis (quantitative).

Tosdal and Richards (2001) provide a useful compilation and summary describing the tectonic setting of porphyry copper deposits. Their results provide a broad framework for viewing porphyry deposits within convergent margin settings ranging from orthogonal compression to extension and the more common intermediate stress conditions of transpression to transtension. They argue that conditions are favorable for the development of porphyry copper deposits in certain ranges or phases of transpression to transtension. When compressive stress is locally relaxed, magmatic stocks are emplaced. They also noted that fault jogs may generate areas of extension that could serve as optimum loci for the ascent of magma and potential development of porphyry copper mineralization. These ideas are similar to those developed and expanded on by Berger and Drew (1997), Berger and others (1999), Drew and others (1999a,b), and Drew and Berger (2001, 2002).

The Tectonic Deposit Occurrence Model

The model presented here was initially developed and first applied to assess the undiscovered porphyry copper and polymetallic vein resources of northern Hungary (Berger and Drew, 1997; Drew and others, 1999a). This model was derived from the observation that porphyry copper and polymetallic vein deposits are genetically related and occur in close spatial and temporal association in the principal deformation zones (PDZ) of strike-slip fault systems and, in particular, in fault duplexes (fault jogs or stepovers; fig. 2). The model draws on summaries of field-based observations (Seraphim and Hollister, 1976; Titley and Beane, 1981) and the empirical descriptive model of Cox (1986). It was expanded by incorporating theoretical studies of the behavior of strike-slip fault systems (Segall and Pollard, 1980) and studies of heat dissipation and the mechanics associated with intrusive rocks (Norton, 1982; Sonder and England, 1989).

Emplacement of a Porphyry Stock and Deposition of Porphyry Mineralization

One of the most striking field observations concerning porphyry stocks was made by Seraphim and Hollister (1976). Mineralized porphyry stocks are relatively small, approximately 1 square kilometer, as compared with most plutonic bodies, and are often nearly circular. In addition, these stocks can rise to very shallow levels in the crust, having vertical extents of as much as 7 kilometers (km).

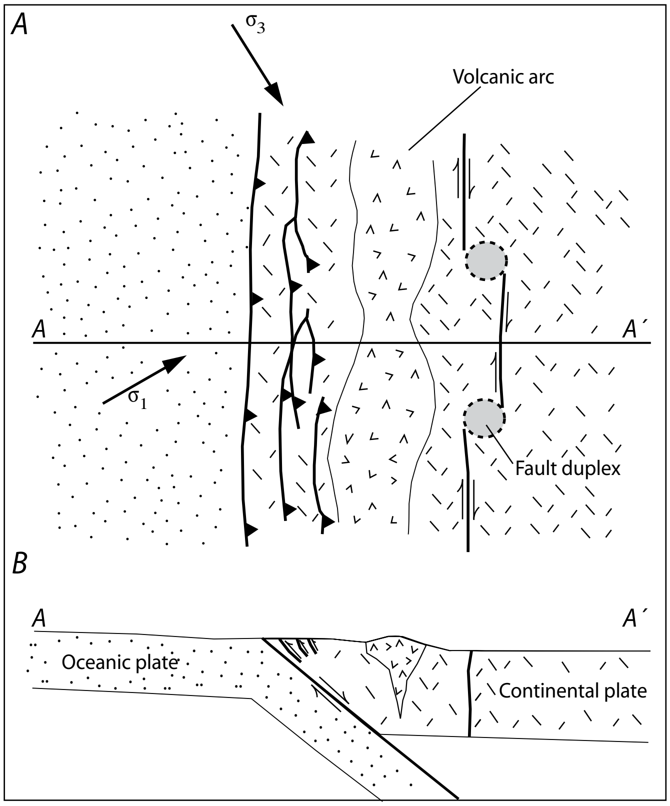

Figure 2. Location of strike-slip fault duplex structures along an active tectonic-plate margin. Strike-slip fault is right lateral and has left and right stopovers. *A*, Map view; *B*, Cross section. Modified from Bally and Oldow (1985). σ_1, maximum principal stress; σ_3, minimum principal stress.

This presents a seeming contradiction. How can a long, narrow cylinder of magma be maintained in the active tectonic environment of a strike-slip fault system? When stress in the far field is released in the PDZ of a strike-slip fault system, a wide variety of strain features form and evolve (fig. 3). These strain features include a complex array of reverse and normal faults, fault duplexes, folds, and flower structures. As magmas are generated above the subducting plate and rise in the crust, these strain features form the necessary channelways through which magma can be focused into dikes and stocks. An entire duplex (figs. 2, 3) may be filled with a mixture of volcanic rocks and volcaniclastic sedimentary rocks. Strain partitioning occurs because of the complex relation between the brittle deformation in a strike-slip fault duplex at the surface to the brittle-ductile transition at lower depths (fig. 4). The initial phase of intrusion and development of a mineralizing system begins in the crustal plate above the subducting slab as far-field stress is dissipated in strike-slip fault duplexes. A model study by Segall and Pollard (1980) showed that as stress is transferred from one master fault tip to another across a duplex, zones of tensional fracturing (areas without shear) are created at the fault tips in compressional and extensional duplexes (fig. 5*A*, *B*, respectively). In addition, in an extensional duplex, tensional fracturing occurs in an annulus-shaped region (fig. 5*B*) located between the fault tips. With emplacement of the magma in the duplex structure, the surrounding wall rock temperature is elevated to mesothermal levels thereby creating the conditions (locally ductile) for the creation of a self-sealing chemical “reaction containment” vessel (Drew and Berger, 2002; Drew, 2003). The reaction containment vessel consists of the apical area of the stock and the

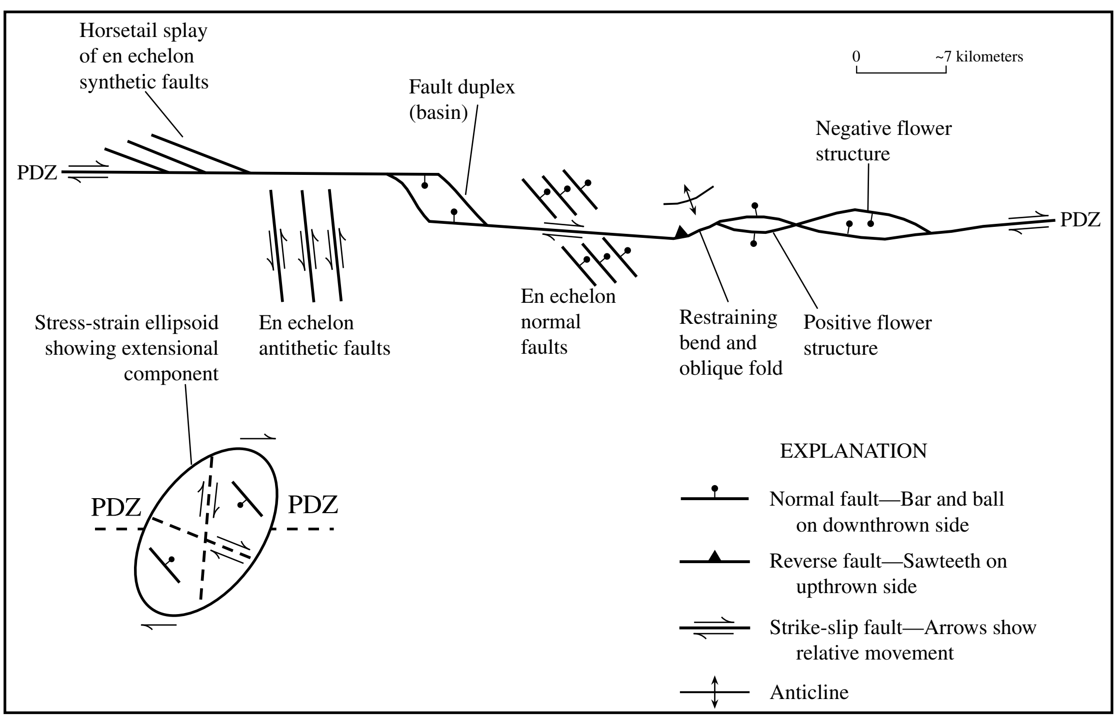

Figure 3. Some of the strain features developed in the principal deformation zone (PDZ) of a strike-slip fault system. Modified from Harding and others (1985).

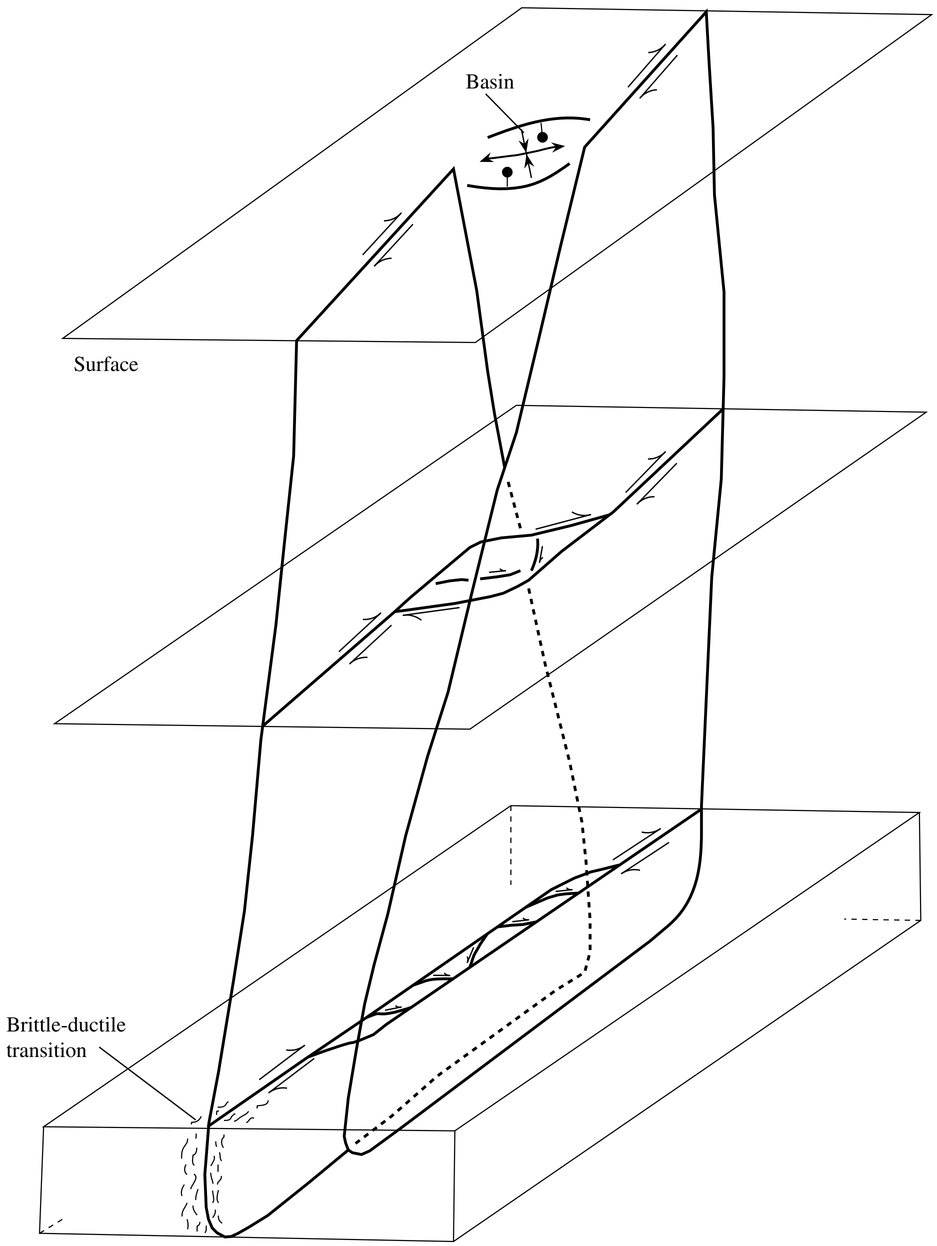

Figure 4. Possible relation between deformation at the surface, intermediate, and at the brittle-ductile transition in a strike-slip fault zone. Modified from Swanson (1989).

adjacent encapsulating wall rock and provides the necessary conditions for carapace development, hydrofracturing, and focusing of hydrothermal fluid flow. The far-field stress was effectively neutralized during the deposition of most porphyry copper deposits. In a few porphyry systems, however, most noticeably at Chuquicamata, Chile, much of the “porphyry” ore body is trapped in an extensional-shear mesh as veins inside the body of a duplex (Sibson, 1987).

When new magma is no longer being emplaced into the magma chamber and heat dissipates in the stock and surrounding wall rock, the likelihood of throughgoing brittle fracturing in the duplex and in the vicinity of the cooling porphyry increases as the far-field stress regains structural dominance. Polymetallic veins often crosscut and are often found with porphyry copper deposits and are deposited in a network of tension and shear fractures that develops in this retrograde thermal environment as brittle fracturing destroys the integrity of the reaction containment vessel (fig. 6*A*–*C*). The breaching of the containment vessel is accompanied by changes in the hydrothermal fluid system from being largely magmatic to a mixed magmatic-meteoric phase of hydrothermal fluid flow.

Burnham’s (1979) classic geochemical model for the formation of porphyry copper deposits can be placed within the tectonic framework discussed above. In his model the magma in the cylinder goes through stages of hydration during the process of its solidification (fig. 6). As the magma solidifies,

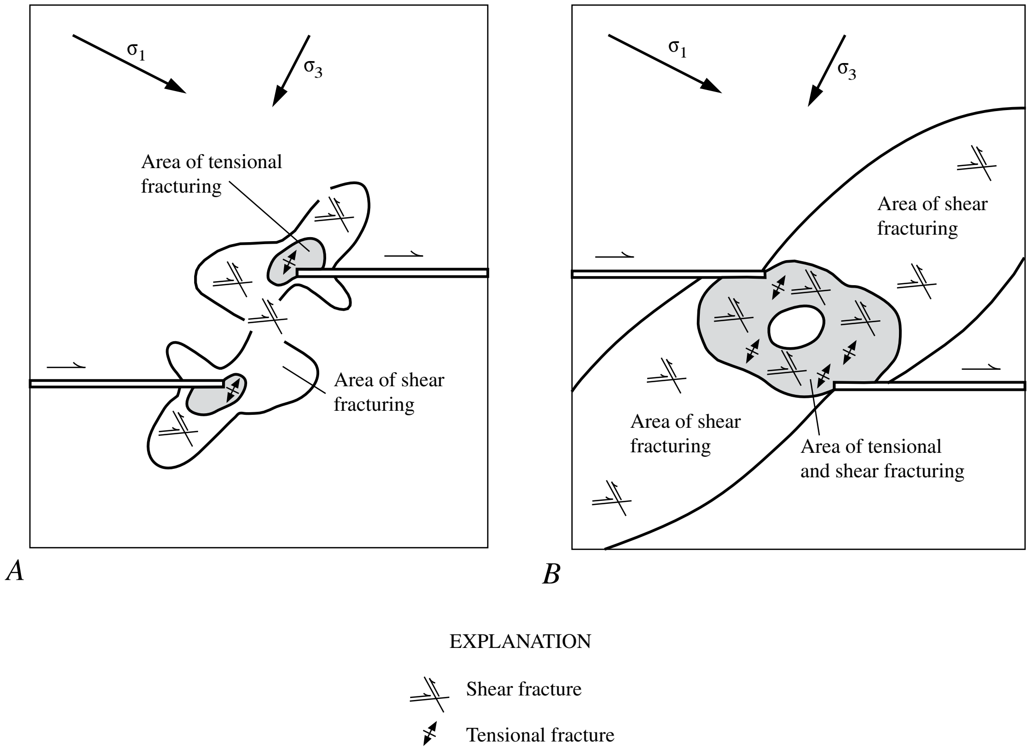

Figure 5. Areas of tensional and shear fracturing between the tips of two interacting master strike-slip faults in a right-lateral system. *A*, Compressional duplex; *B*, Extensional duplex. Modified from Segall and Pollard (1980). σ_1, maximum principal stress; σ_3, minimum principal stress.

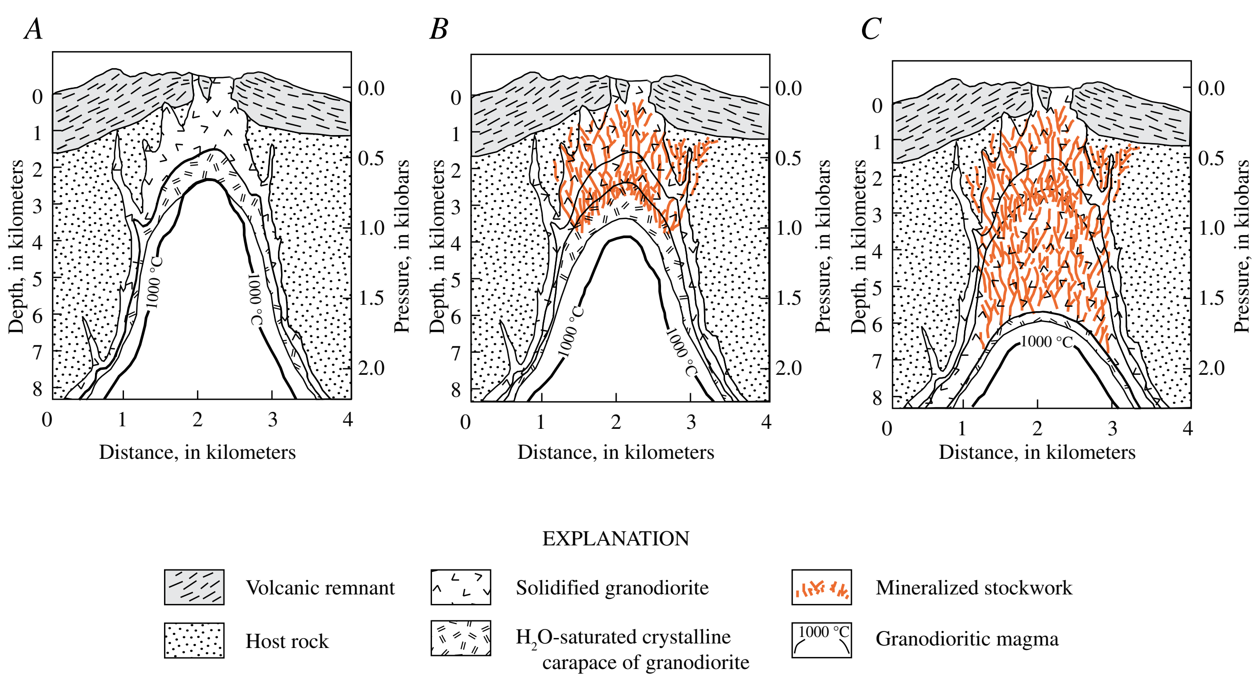

Figure 6. Schematic cross section through a hypothetical granodiorite porphyry stock and associated dikes at three progressive stages of their solidification. Modified from Burnham (1979).

the melt becomes more hydrous, pressure rises in the magma, and boiling occurs (fig. 6*A*). These processes are accompanied by volume changes that cause fracturing of the recently solidified carapace and associated deposition of quartz, potassium feldspar, and copper and iron sulfides (fig. 6*B*). After release of the pressure, the system is resealed by the deposition of quartz and feldspar. With further solidification, the hydration cycle repeats, the newly deposited carapace is fractured, and an additional assemblage of gangue and sulfide minerals is deposited (fig. 6*C*). All of these reactions occur during the period when the column of magma is in a stable tectonic configuration as discussed above.

We can gain additional insight into the location of these porphyry copper and polymetallic vein deposits within a duplex from model studies by Rogers (1980), Segall and Pollard (1980), and Connolly and Cosgrove (1999). Empirically, in extensional duplexes the corners and edges appear to be the preferred sites of porphyry emplacement.

In the initial stage of an extensional duplex's development (fig. 5*B*), the tips of the master faults do not overlap. In the compressional duplex, the area where tensional fracturing can occur is limited to a relatively small area at the tips of the two master faults (fig. 5*A*). Although a compressional duplex (fig. 5*A*) can be favorable for porphyry emplacement, we usually find porphyry copper deposits in extensional duplexes (fig. 5*B*). This is most likely a consequence of the fact that in well-documented strike-slip fault systems the sense of stepping is predominantly releasing and, therefore, favorable for the formation of extensional duplexes (Parkinson and Dooley, 1996).

The results of the modeling of extensional duplexes suggest that tensional fracturing occurs within a much larger area than that occurring in compressional duplexes because it is associated with shear (fig. 5*B*). These results of Segall and Pollard (1980) suggest that even with no fault overlap there may be many sites in the intra-tip area that are favorable for the emplacement of porphyry stocks. Rogers (1980) modeled the evolution of extensional fault duplexes and pull-apart basins at various degrees of overlap (fig. 7). As the degree of overlap increases, the area of tensional fracturing (the intra-tip area), where sedimentary basins occur, is subsequently rotated and separated into two basins that migrate spatially. The areas of normal faulting are under extension, volcanic rocks and magmatic stocks are emplaced, and volcaniclastic and other sediments are deposited. Multiple sites may exist in the duplex for porphyry copper systems to form during the progressive evolution of strike-slip fault duplexes.

More recently, Connolly and Cosgrove (1999) have expanded the earlier research of Rogers (1980) and have included a brief discussion of the application of their study to the occurrence of mineral deposits. Their principal focus, like that of Rogers, was on building a model to aid in petroleum exploration. Their study shows that when the overstep is twice the distance between the master strike-slip faults (fig. 7*D*; Rogers, 1980), tensional fracturing is pervasive (fig. 8). This area has the map pattern of an annulus whose outer boundary is defined by the fault boundaries of the duplex (fig. 9). Connolly and Cosgrove (1999) also show the locations of maximum fluid flow in the duplex, which are focused at two relatively small areas on the corners of the duplex.

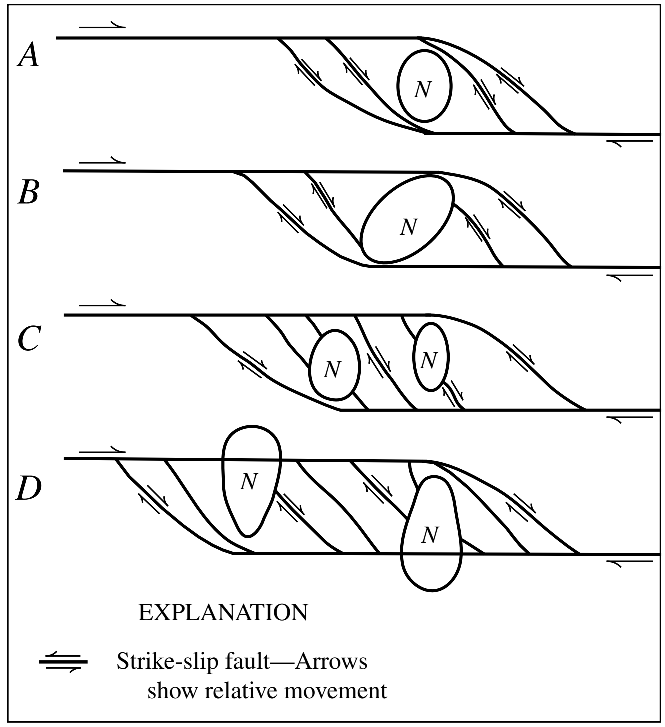

Figure 7. Diagram showing the possible evolution of an extensional fault duplex (pull-apart basin) where the overstep increases from neutral to twice the vertical distance between the master faults. Areas labeled "N" are areas of normal faulting (extensional areas) where sedimentary basins have occurred. Modified from Rogers (1980).

The possible distribution of tensional fracturing inside the annulus-shaped region may be discontinuous (Connolly and Cosgrove, 1999). Thus, the annulus-shaped region is, in general, more favorable than the middle of the duplex for the intrusion of a porphyry stock and the development of porphyry mineralization. Their model also suggests that tensional fracturing is rare at sites of neutral overlap and that fracturing increases as the degree of overstep increases. This is a very useful concept when making a resource assessment, for it creates a basis to evaluate, by the degree of overlap, the favorability of a group of duplexes in a strike-slip fault system. This model also provides information needed to identify areas within a duplex that have higher probabilities for stock emplacement. The author speculates that faults in the area of the annulus (fig. 9) are an interconnected mosaic of extensional duplexes and positive and negative flower structures (fig. 10).

Deposition of Polymetallic Veins

The tectonic model describing the porphyry copper system must include how closely associated epithermal polyme-

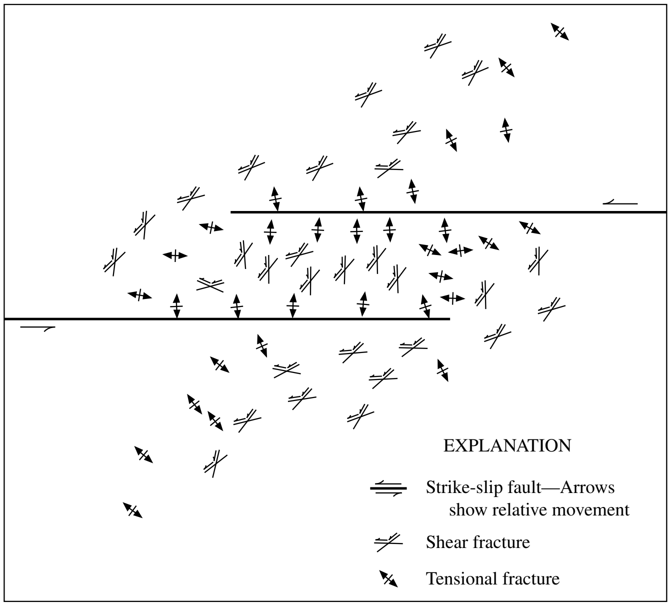

Figure 8. Tensional and shear fracturing in and near a strike-slip fault duplex. Modified from Connolly and Cosgrove (1999).

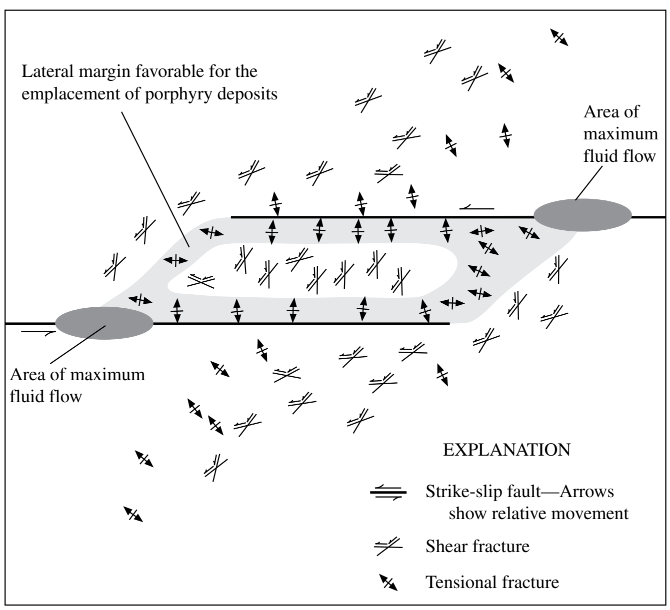

Figure 9. A strike-slip fault duplex showing the region most favorable for the tensional fracturing with maximum fluid flow. This area would be favored for the intrusion of porphyry stocks and the occurrence of porphyry copper deposits. Modified from Connolly and Cosgrove (1999). Positive and negative flower structures can occur in the area of the annulus.

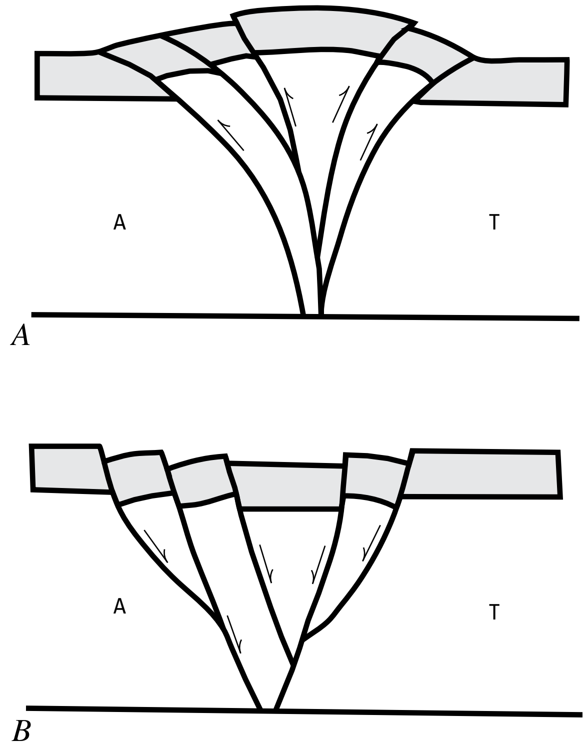

Figure 10. Diagrams showing cross sections through (*A*) positive and (*B*) negative flower structures. A, movement is away from viewer; T, movement is toward viewer.

tallic veins form. These veins usually contain low tonnages of high-grade ore comprising copper, gold, lead, silver, and zinc. In some mining districts these veins have high commercial value (Bliss and Cox, 1986).

The physical proximity of polymetallic veins and porphyry copper deposits has been considered, for the most part, to be coincidental. Here, this association is genetic. Porphyry copper and polymetallic vein deposits form a family of mineral deposits initially of magmatic origin (porphyry copper) that systematically progresses over time and space toward mineral deposits of mixed magmatic-meteoric origin (polymetallic veins) (Berger and others, 1999; Drew and others, 1999a; Drew and Berger, 2001; Drew, 2003).

The tectonic model developed here must explain the connection between the spatial and temporal occurrence of the porphyry stock (and its primary mineralization) and polymetallic vein mineralization. An understanding of how the structural regime changes within the duplex from one suitable for the emplacement of a porphyry stock to one suitable for the deposition of vein mineralization is critical. The overall tectonic model must account for the “quiet” tectonic phase within the duplex, when the integrity of the reaction containment vessel is maintained and single or multiple intrusions can solidify, and the porphyry mineralization can occur (fig. 6).

Crosscutting relations seen in the field often indicate that polymetallic veins formed after emplacement of the porphyry stock and associated mineralization (fig. 11). The type of ore in the polymetallic veins can vary widely from high to low sulfidization. The veins contain complex suites of ore and gangue minerals and have isotopic fluid signatures that range from nearly magmatic to predominantly meteoric.

Deposition of porphyry mineralization requires local areas of extension without shear. The deposition of polymetallic veins requires active shear and tensional fracturing in an

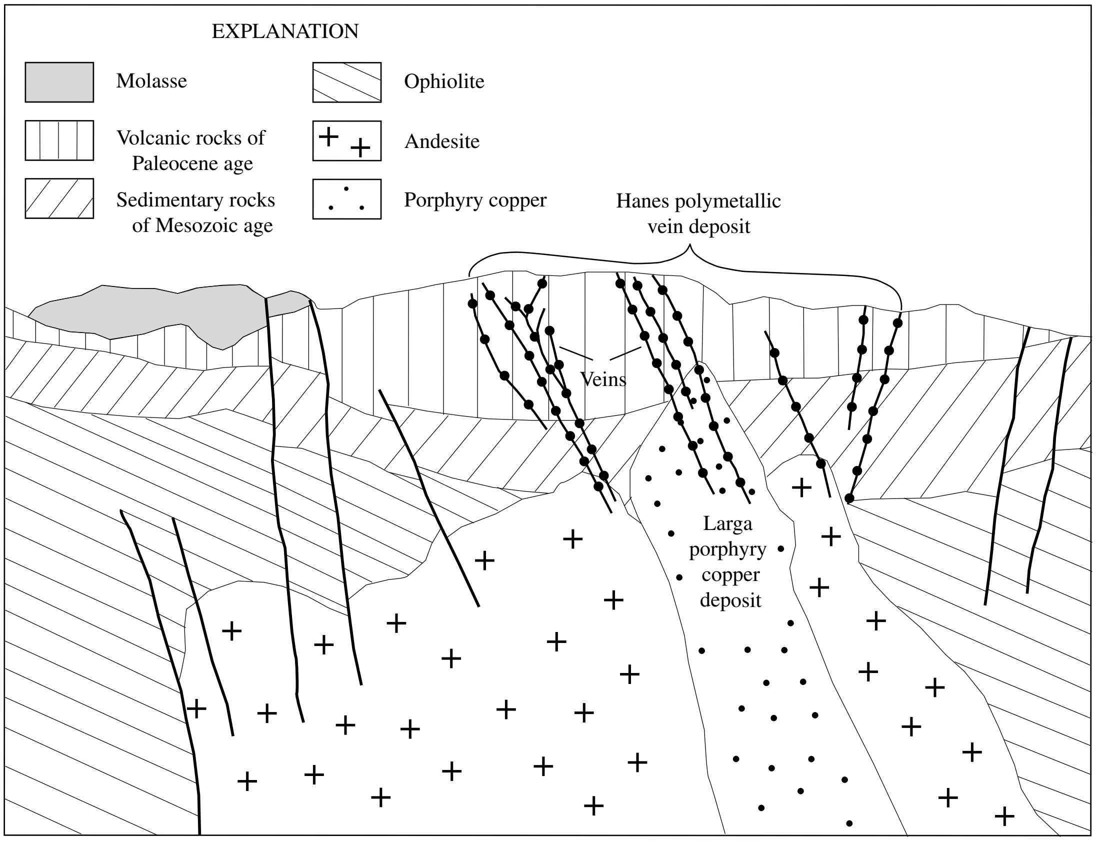

Figure 11. Cross section through the Larga porphyry copper deposit, Apuseni Mountains, Romania, showing the crosscutting and other spatially associated polymetallic veins. Modified from Borcoş (1994).

extensional-shear mesh (fig. 12). Berger and others (1999), Drew and others (1999a), Drew and Berger (2001, 2002), and Drew (2003) have shown that deposition of polymetallic veins occurs in a duplex after the far-field stress becomes predominant and the reaction containment vessel is ruptured. Within the later polymetallic vein segment of mineralization, the composition of the veins generally evolves from an earlier phase of high sulfidization, when the hydrothermal fluids are from a magmatic source, to a later phase of low sulfidization reflecting a mixed magmatic-meteoric or meteoric fluid source.

The mechanical details of how zones of extension and shear fractures change or form into a functioning extensional-shear mesh are not well understood. There is, however, extensive literature that illustrates how the mesh functions (McKinstry, 1948; Hill, 1977; Sibson, 1986, 1987, 1989). McKinstry (1948) assembled descriptions of the behavior of a large number of mineralized and barren veins and fractures in polymetallic metal mines in the Western United States, Mexico, Peru, Australia, and elsewhere. He noted that a single fracture can change along its course from tension to shear and end at a sharp point. Tension fractures often occur in closely spaced parallel sets. McKinstry (1948) described the polymetallic vein deposits at Oatman, Ariz., as consisting of two parallel veins that join and then separate and become parallel again in a manner similar to the design of a chicken-wire mesh. He also recognized the collection of parallel veins in the structure that we call today a strike-slip fault duplex. McKinstry (1948) labeled the structure a cymoid loop and connected it to a set of horsetail veins that are common terminations of a duplex structure.

McKinstry (1948) modeled a fault that had right-lateral and right-stepping movement that changed its' strike in a clockwise manner and then reoriented itself back to the main strike direction (fig. 13*A*). This type of slip along a fault creates a favorable opening for the deposition of ore minerals, whereas the opposite movement is unfavorable for ore deposition (fig. 13*B*). McKinstry came very close to recognizing the alternating tensional and shear segments of the extensional-shear mesh that was later developed by Hill (1977) as the mechanism that localizes dikes in dike swarms and by Sibson (1986, 1987, 1989) as the mechanism that traps the ore shoots in polymetallic veins. Additionally, McKinstry anticipated later models of the mechanical behavior of the mesh. For example, areas of favorable permeability (fig. 13*B*) correlate with the fault duplex basin and negative flower structures (figs. 3, 10*B*), and areas of unfavorable permeability (fig. 13*B*) correlate with compressional structures and positive flower structures (figs. 3, 10*A*).

Our current understanding of the mechanics of the extensional-shear mesh had its origin in the study of earthquakes associated with strike-slip fault duplexes (Hill, 1977). Swarms of dikes are commonly found in the eroded volcanic

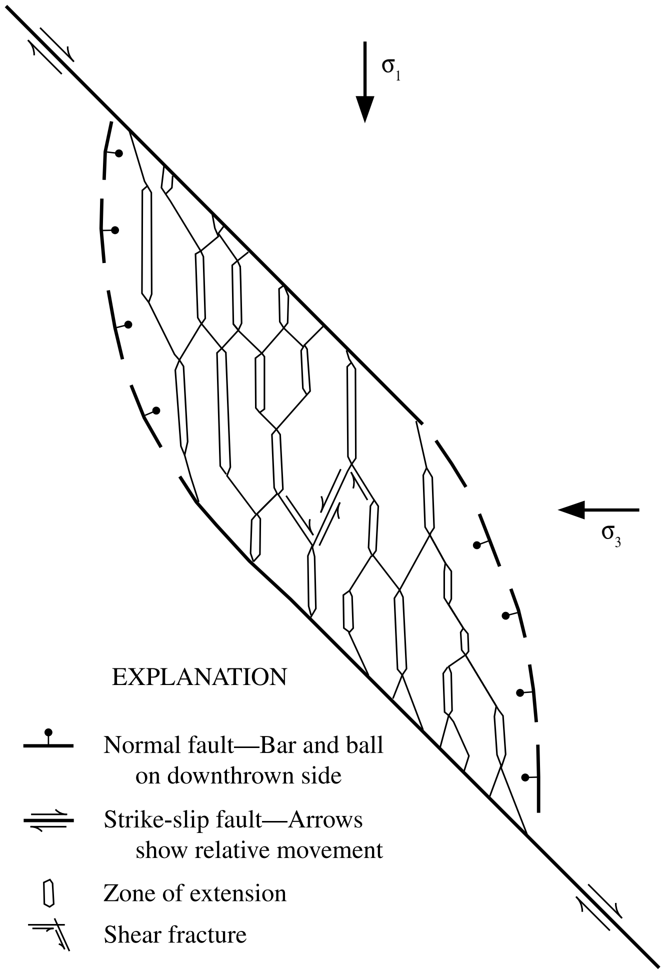

Figure 12. The extensional-shear mesh of a brittle fracture within a strike-slip duplex (Sibson, 1985). Polymetallic veins are deposited along zones of extension connected by shear fractures. σ_1, maximum principal stress; σ_3, minimum principal stress.

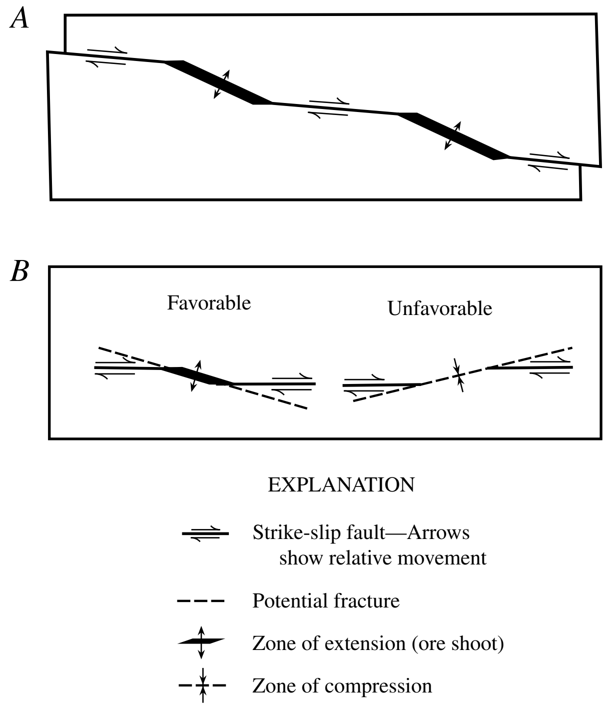

Figure 13. Schematic diagram showing movement on a strike-slip fault. *A*, Fault with alternating segments of shear and extension; *B*, Comparison of a favorable movement for vein deposition (right-stepping fault segment) with an unfavorable (left-stepping fault segment) in a strike-slip fault. Modified from McKinstry (1948).

fields whose emplacement can be related to the release of tectonic stress inside an extensional fault duplex. The dikes were deposited in extensional voids (fig. 14) created when earthquake energy was absorbed in the duplex. At the summit of the Kilauea Volcano, Hawaii, an inferred swarm of dikes is aligned with the maximum principal stress (σ_1), and focal mechanism studies indicate that strike-slip faulting was the main mode of failure (Hill, 1977). Using an earlier model study by Pollard (1973), Hill created the schematic diagram (fig. 15) that would later be known as the extensional-shear mesh (Sibson, 1985, 1986, 1987, 1989). As used to describe the earthquake and magmatic behavior at Kilauea, the mesh is activated when the seismic energy from an earthquake originating somewhere along the master northwest-trending strike-slip fault system enters the duplex (figs. 14, 15). Once the energy has entered the duplex, the rocks rupture by strike-slip faulting, the mesh opens, and magma flows into the extensional segments. After the energy has been absorbed,

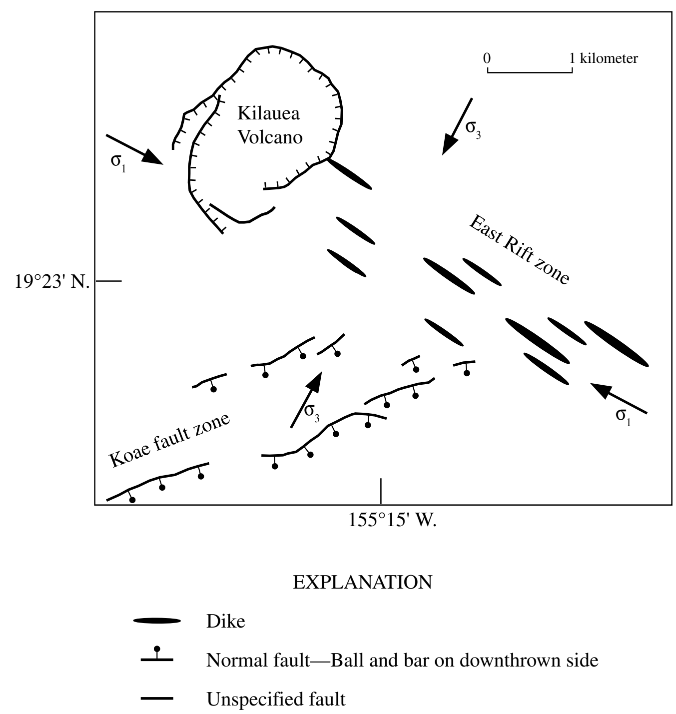

Figure 14. Map of the summit region of Kilauea Volcano, Hawaii, showing inferred dike distribution. Modified from Hill (1977). σ_1, maximum principal stress; σ_3, minimum principal stress.

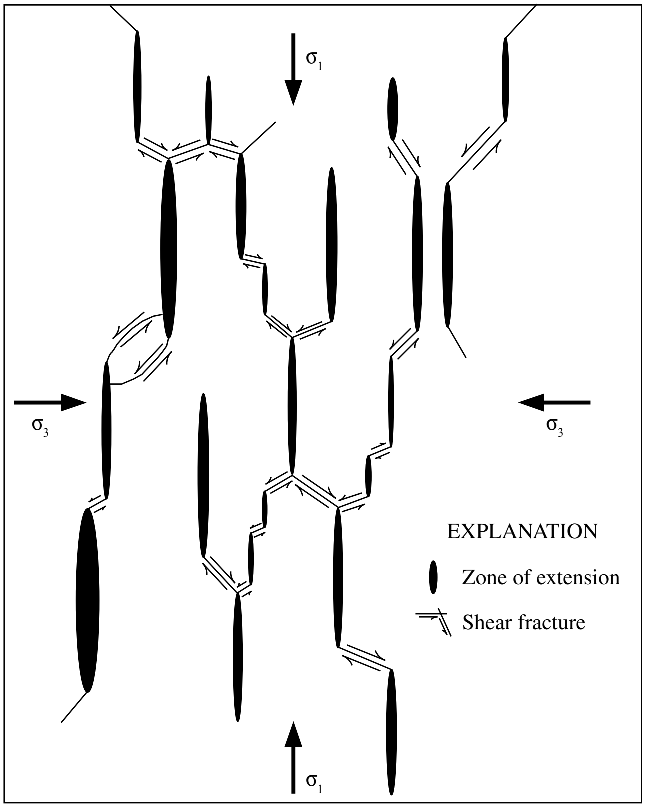

Figure 15. Schematic representation of shear fractures and zones of extension filled by basaltic dikes. Modified from Hill (1977). σ_1, maximum principal stress; σ_3, minimum principal stress.

the mesh closes and traps the magma as dikes. When the next earthquake occurs, this cycle is repeated.

In summary, once the reaction containment vessel (fig. 6) is breached by throughgoing brittle fracturing in an extensional-shear mesh, the hydrothermal system is open to nonmagmatic sources of zinc, lead, and other components that have been leached by incoming meteoric waters from the rocks surrounding the porphyry stock. The hydrothermal fluid is trapped in the extensional-shear mesh as vein ore during repeated cycling of the seismic pumping system triggered by earthquakes. To be effective at trapping ore, the mesh must be sealed except during those brief moments of geologic time when energy from an earthquake has opened it and allowed hydrothermal fluid to enter.

Sibson (1987) used two deposits to demonstrate the important role that the extensional-shear mesh has played in hosting ore bodies. The first is the Chuquicamata copper deposit in Chile (fig. 16*A*), which is usually considered to be the world's largest porphyry copper deposit. Instead of being hosted in the normal porphyry setting (fig. 6), the granodiorite and quartz porphyry stock and "porphyry" ore at Chuquicamata fill the entire fault duplex (fig. 16*A*). This is a variation of the tectonic occurrence model where only the corners and edges are the preferred sites for the porphyry deposits. Hollister (1974, 1978) noted that Chuquicamata is an excellent example of a porphyry copper stockwork developed in a set of conjugate fractures (an extensional-shear mesh) between major strike-slip faults. He further noted the strong evidence that the regional strike-slip fault system had controlled the emplacement of the porphyry stock and the hydrothermal deposition of quartz and sulfides. As the magmatic system crystallized and retreated, the mineral deposit was not trapped in a stockwork created by the repeated fracturing of the carapace (fig. 6). This conclusion also is supported by Guilbert and Park (1986, p. 420–422) who described Chuquicamata as a stockwork developed in the shear couple between two shear zones (master strike-slip faults). Lindsay and others (1995) similarly noted that this mesh was functioning at shallower levels in a divatoric stress field (shear forces) trapping the ore above the retreating magma.

Sibson's (1987) second example is the Martha lode system, Waihi, New Zealand, where an extensional-shear mesh hosts gold-bearing veins. The ore shoots trapped in tensional segments of the extensional-shear mesh are clearly visible in plan and cross sectional views of the mine (fig. 16*B*). The extensional-shear mesh, activated by seismic energy, traps hydrothermal fluid in ore shoots as a three-dimensional network of tensional and shear fractures.

Association Between Strike-Slip Faulting and Magmatism in Convergent-Margin Magmatic Arcs

Oldow and others (1990) proposed that strike-slip faults that cut through the continental crust into the mantle are present in virtually all orogenic belts and, in most, are at least partly coeval with contractional deformation (thrust faults and nappe stacks). Furthermore, at convergent margins and during continental collisions, oblique convergence is the main source of the energy necessary for the simultaneous development of thrust and strike-slip faults. Additionally, Oldow and others (1990) proposed that during subduction, the synchronous displacement along the thrust and strike-slip faults is linked to a basal detachment fault upon which the lithosphere and, conceivably, the upper mantle "float" directly above the subducting plate in the forearc and up to several hundred kilometers above the backarc.

Glazner (1991) argued that plutonism and volcanism may be decoupled, and the presence of a volcanic arc may not indicate a batholith at depth. Furthermore, plutonism can be facilitated by strike-slip faulting that helps solve the well-known "room problem" by allowing plutons to be emplaced passively at releasing bends (extensional fault duplexes) in strike-slip fault systems. Grocott and others (1994) accepted Glazner's hypothesis for contractional subduction settings, when the convergence rate exceeds the subduction rate. Conversely, when the arc is under extension, room for emplacement of plutons is created by extension on normal faults and within duplexes in transtensional strike-slip fault systems. Grocott and others (1994) showed that the Andean plate boundary, an extensional

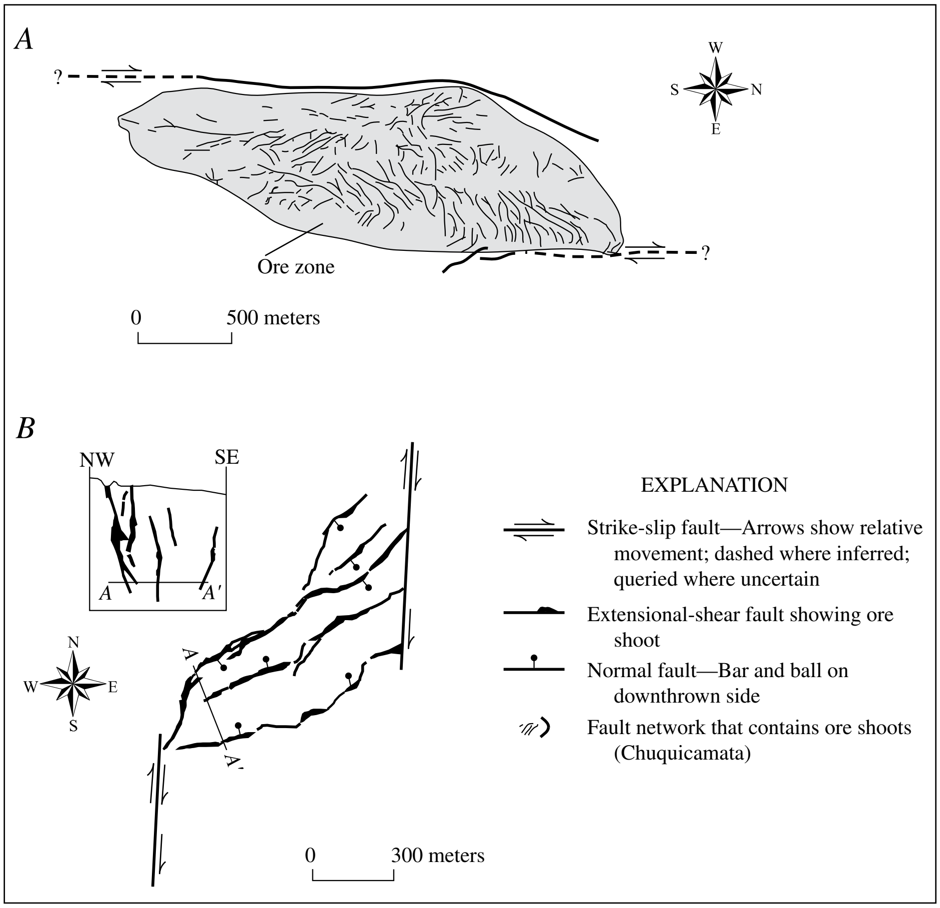

Figure 16. Examples of mineralized strike-slip fault duplexes. *A*, Map view of Chuquicamata, Chile; *B*, Martha lode system on the #9 level, Waihi, New Zealand. Modified from Sibson (1987).

arc, has plutonism when the extensional fault systems are active and volcanism when they are dormant.

De Saint Blanquat and others (1998) noted that motion on strike-slip faults in magmatic arcs is linked to the angle of plate convergence. In the absence of magmatism, they noted strike-slip faulting occurs most effectively at low angles (<20°) of plate convergence. However, in many magmatic arcs the angle of convergence ranges from 50° to 85°, and a substantial proportion of the contraction is partitioned by strike-slip faulting. In fact, strike-slip faulting occurs in magmatic arcs even at or near orthogonal convergence angles. Clearly, in transpressional magmatic arcs, fault kinematics and magmatism are intricately linked. As magma rises in an arc, strike-slip faulting is more easily accommodated and more space occurs for ascending magma. Magmas rise in magmatic arcs through a combination of buoyancy forces related to density contrasts and tectonic overpressuring induced by tectonic deformation. This tectonic overpressuring occurs when the horizontal tectonic load is partially converted into a vertical driving force (de Saint Blanquat and others, 1998).

They concluded that the overpressuring of the magma initiates the strike-slip movement and, therefore, causes the pull-apart regime in the magmatic arc. In addition, deformation in the upper crust of the magmatic arc is best represented as a double wedge prism with the classic geometry of a flower structure; in other words, thrust faults emerge from a central strike-slip fault and verge in opposite directions (fig. 17). Strike-slip and thrust faulting are linked together by basal detachment faults and a vertical thermally weakened deformed zone in the lithosphere. In this zone the ascent of magma is linked with strike-slip faulting.

Orogenic Collapse, Strike-Slip Faulting, and Basin Development

Certain fault duplexes that develop in magmatic arcs and orogenic belts can be confused with the fault duplexes that are permissive for porphyry copper and polymetallic vein deposits. These include external pull-apart basins (terminology of Willingshofer and others, 1999, and Willingshofer, 2000) in the Alps and central Europe that are associated initially with low-angle detachment faults. Subsequently they occur with strike-slip faulting developed during the extensional collapse of an orogen (Ratschbacher and others, 1993; Neubauer and others, 1995; Willingshofer and others, 1999). These so-called external

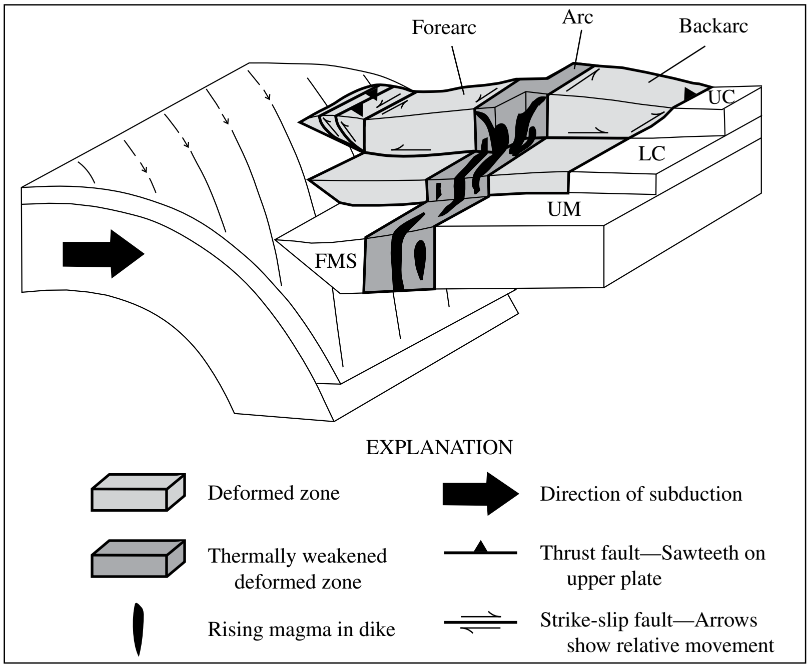

Figure 17. Model for kinematics and heat distribution in a contractional magmatic arc. UC, upper crust, a zone of strike-slip partitioning and distributed shearing; LC, lower crust, a zone of distributed shearing; UM, upper mantle, a zone of localized shearing; FMS, forearc mantle sliver, a zone of orogen-parallel translation of the lithospheric mantle below the forearc. Modified from de Saint Blanquat and others (1998).

pull-apart basins generally are not permissive for the occurrence of porphyry copper and polymetallic vein deposits because they are rooted in the nappes and, therefore, do not provide an effective channelway for the ascent of subduction-related magma. These external basins are filled with a fining upward clastic sedimentary sequence, conglomerate to turbidite, with occasional marly limestone, limestone, and coal beds (Willingshofer and others, 1999). According to Willingshofer and others (1999), these basins form on the top of nappe sequences facing the actively subducting oceanic plate in the forearc.

Internal pull-apart basins, a second group of fault duplexes delineated by Willingshofer and others (1999), form on previously thickened crust in the central parts of orogens and may contain volcanic and intrusive rocks. These basins can be permissive for the occurrence of deposits in the porphyry copper and polymetallic vein family. These more centrally located basins are equivalent to the extensional duplexes (figs. 2, 5*B*, 7–9) located in the “thermally weakened deformed zone” (fig. 17).

The strike-slip faults associated with basin development during orogenic collapse and the subsequent orogen-parallel extension must be carefully examined during resource assessments. Strike-slip fault systems associated with the development of external basins should be classified as nonpermissive for the occurrence of porphyry copper and polymetallic vein deposits.

Application of the Model to Certain Ore Fields in Central Europe

Late Cretaceous Orogen—Banat-Timok-Srednogorie Region

The Banat-Timok-Srednogorie region extends over 750 km from southern Romania, through eastern Serbia, and across the length of Bulgaria (fig. 18). This region is known in the literature by many names, including the Banatitic Magmatic and Metallogenic Belt (Berza and others, 1998). However, this report will retain the label associated with the geographic names of the areas being discussed. The Banat-Timok-Srednogorie region contains seven significant porphyry copper deposits, five of which are in production today (table 1). Additionally, there are many polymetallic vein deposits, of which a few are in production today, and many porphyry copper, polymetallic vein, and skarn prospects (Ciobanu and others, 2002). The subduction-related magmatism associated with the various porphyry and hydrothermal deposits was calc-alkaline and spanned the period 90 to 60 Ma (Ciobanu and others, 2002).

The tectonic history of the Carpatho-Balkan region during the Late Cretaceous and Early Tertiary is complex because

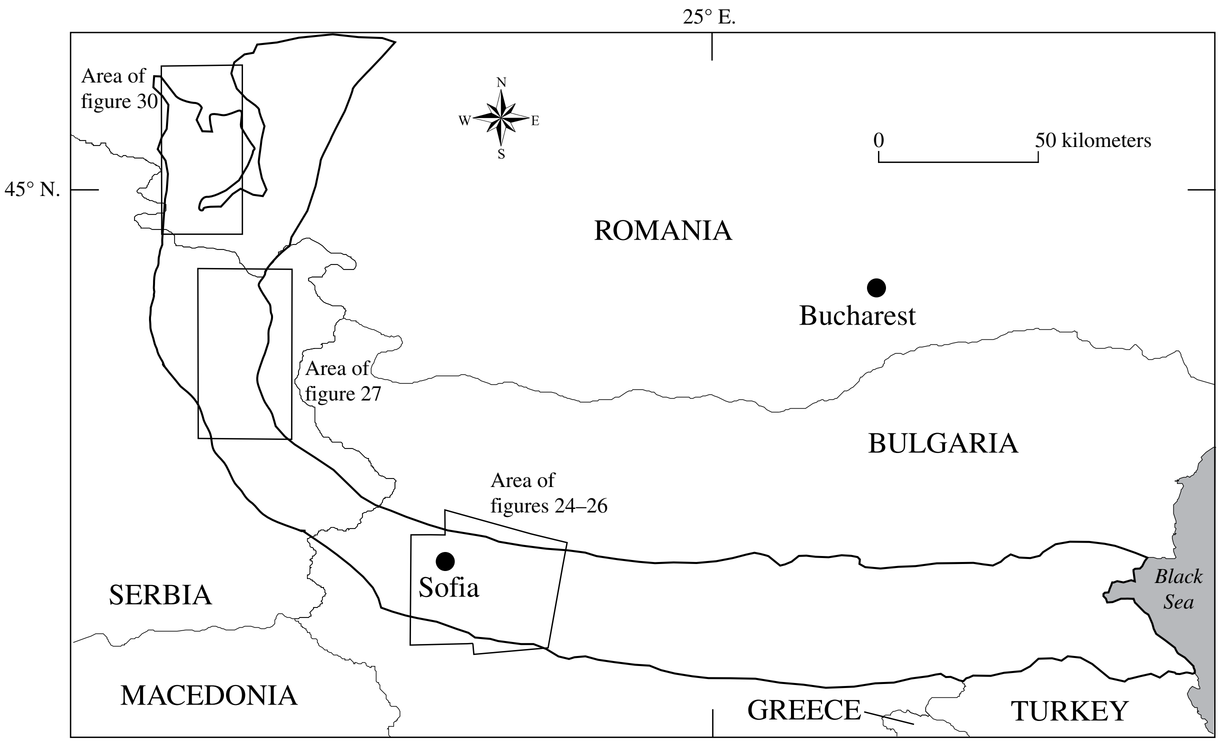

Figure 18. Location of study areas in the Banat region (Romania), the Timok magmatic zone (Serbia), and a part of the central Srednogorie region (Bulgaria). See figure 1 for location. Compiled and modified from Codarcea and Răileanu (1968), Yugoslavia Federal Geological Institute (1970), Bulgarian Institute of Academy of Sciences (1973), Council for Mutual Economic Assistance (1977), Bogdanov (1983), and Janković (1990).

Table 1. Tonnages and grades of porphyry copper deposits of the Banat-Timok-Srednogorie region.

[Data from Singer and others (2002)]

Name of deposit	Tonnage, in million metric tons	Copper, in percent
Banat region, Romania		
Moldova Nouă	500	0.35
Timok magmatic zone, Serbia		
Majdanpek	1,000	0.60
Velki Krivelj	750	0.44
Bor	450	0.60
Srednogorie region, Bulgaria		
Elatsite	550	0.32
Assarel	360	0.44
Medet	260	0.37

of the number of tectonic plates involved, their associated trajectories, and the multiplicity of contractional and extensional events (Dimitrijević and Grubić, 1977; Burchfiel, 1980; Bergerat and others, 1998). The structural complexity of the region increased in the Tertiary when escape tectonics resulted in extension, rotation, and collision of plates and microplates (Horváth, 1988; Csontos and others, 1992; Csontos and Nagymarosy, 1998; Willingshofer, 2000; Neubauer, 2002).

The present-day geometry of the region (fig. 18) resulted from post-collision tectonics during the Tertiary and has been illustrated by using a block diagram by Csontos and Nagymarosy (1998; fig. 19). Willingshofer (2000) removed the Tertiary structural overprint, resulting in a configuration that suggests an east-west-trending orogen related to the northward subduction of the Vardar oceanic plate under the Tisza-Dacia-Rhodopian block during the Late Cretaceous (fig. 20).

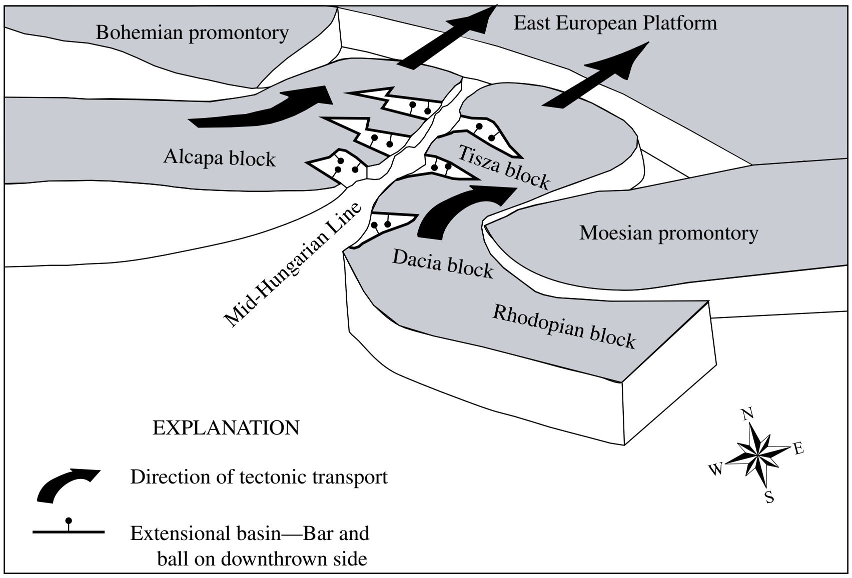

Figure 19. Tectonic model for the late Tertiary evolution of the Carpathian-Pannonian area. Extensional basins and thinned crust shown diagrammatically with tectonic blocks dissected and exploded at the Mid-Hungarian Line, a major transcurrent fault. The Alcapa block is composed of the eastern Alps (Austria), northern and central Carpathian Mountains (Slovakia and northern Hungary), and the northern Pannonian basin (Hungary). The Tisza block is located in southern Hungary; the Dacia block is located in Romania; and the Rhodopian block is located in Bulgaria. Modified from Csontos and Nagymarosy (1998).

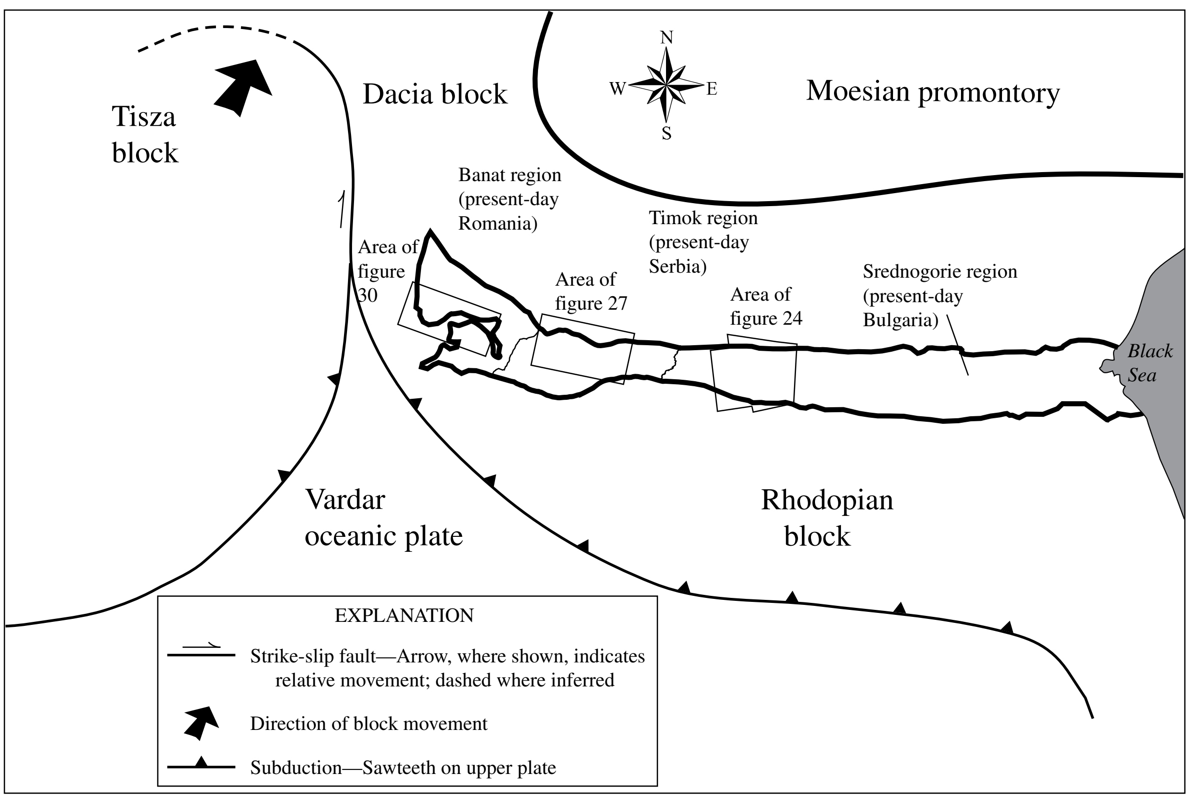

Figure 20. Schematic reconstruction of subduction of the Vardar Ocean under the Rhodopian-Dacia blocks and docking with the Tisza block during the Campanian-Maastrichtian (80–70 Ma). Modified from Willingshofer (2000) and Ciobanu and others (2002). The Banat-Timok-Srednogorie regions and the Black Sea are shown in their relative positions. Geology of the study areas compiled and modified from Codarcea and Răileanu (1968), Yugoslavia Federal Geological Institute (1970), Bulgarian Institute of Academy of Sciences (1973), Council for Mutual Economic Assistance (1977), Bogdanov (1983), and Janković (1990).

Establishing the Sense of Shear in the Orogen

Before the proposed tectonic deposit occurrence model could be applied in the Banat-Timok-Srednogorie region, the regional shear couple that created the strike-slip faulting associated with the eruption of calc-alkaline volcanic rocks and emplacement of coeval porphyry stocks had to be identified. This shear couple is the cause of the local extension and contraction within the strike-slip corridor.

Early researchers in Serbia interpreted a right sense (dextral) of movement in zones of transform and transcurrent faulting in connection with the postulated arrangement and movement of plates and microplates in the Banat-Timok-Srednogorie region during the Late Cretaceous (Dimitrijević, 1974). A right sense of shear was interpreted by Burchfiel (1980) for the collision of the Dacia (present-day Albania, Slovenia, Croatia, Bosnia, Macedonia, and Greece) and Rhodopian (present-day Bulgaria) blocks when the Vardar Ocean was consumed (see fig. 20). Recently, Ivanov and others (2002) in their study of the central Srednogorie region, Bulgaria, also interpret a right sense of shear that's associated with the emplacement of Late Cretaceous magmas.

The Rift Model for the Orogen

Although their model of a continental rift environment is now out of favor, Antonijević and others (1974) and Popov (1987) provide important geologic information for the application of the tectonic deposit occurrence model through their detailed descriptions of the Late Cretaceous faulting, basin development, sedimentation, volcanism, and intrusion in the "rift." The boundaries of the Banat-Timok-Srednogorie region are defined for the most part by straight fault segments (fig. 21). The "rift" thickens and thins along its trend suggesting that a number of extensional duplexes developed in it. Popov (1987) described the formation of grabens by tangential extension and transcurrent faulting along the "rift." These extensional events were followed by intense calc-alkaline magmatism as the transcurrent faults intersected the site of magma supply. In the areas of magmatic activity, grabens formed with volcanic-plutonic rocks in their interiors. This extensional phase of deformation was followed by a compressional phase during which volcanic activity was nearly absent except for some continued magmatic activity in the northwestern part of the "rift." Although Antonijević and others (1974) and Popov (1987) favored a rift environment, the geology they described is much more likely the result of the tectonism and magmatism developed during orogenic transpression within a major strike-slip fault system related to oblique subduction as described above by Oldow and others (1990), Glazner (1991), Grocott and others (1994), and de Saint Blanquat and others (1998).

Application of the Model

In the Banat-Timok-Srednogorie region, the surface expression of strike-slip faulting on maps is associated with the location of known porphyry copper deposits, and to a lesser degree because of data availability, with polymetal-

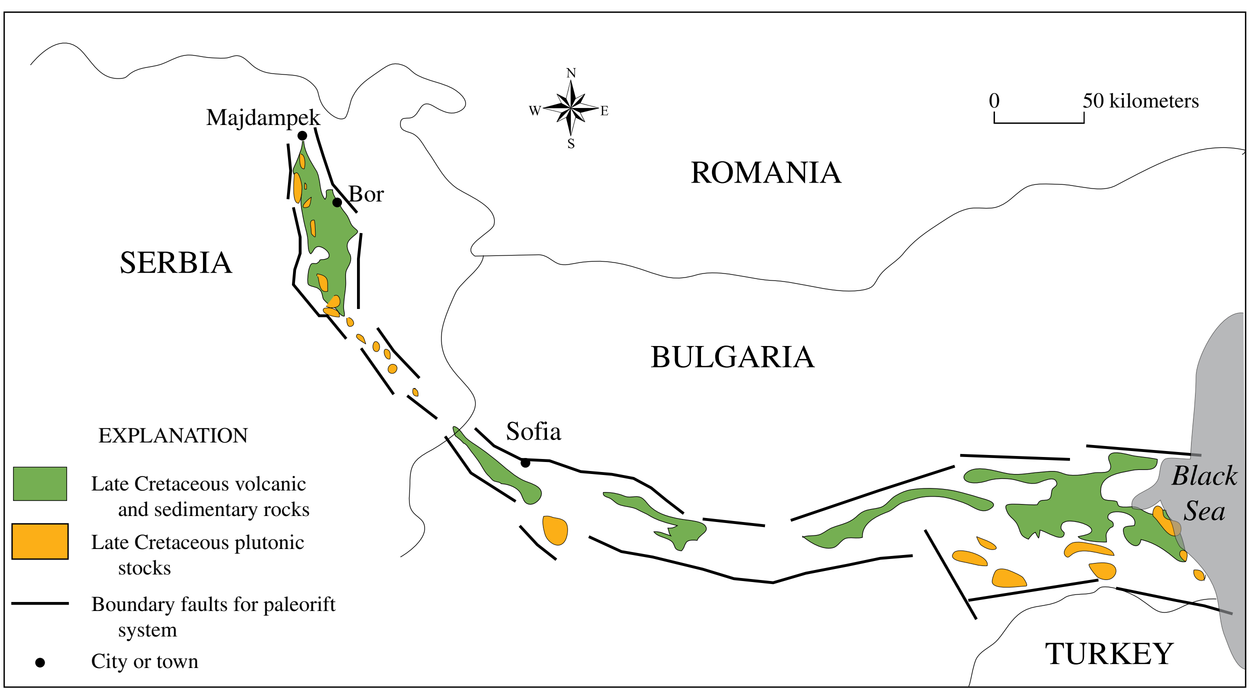

Figure 21. Sketch map showing the Timok-Srednogorie paleorift system in the Serbian and Bulgarian part of the Banat-Timok-Srednogorie region. Modified from Antonijević and others (1974).

lic vein deposits. In addition, where possible, Landsat and ASTER satellite images were used to identify structural features and sites of hydrothermal alteration. The satellite images also were used as a base for compiling tectonic, geologic, and mineral deposit occurrence data from a variety of sources. Most of the maps for the region show many faults but rarely indicate the sense of movement. As mentioned above, the right-lateral sense of movement on the strike-slip faults was generally predicted based on the overall right sense of shear in the orogen. In 1998 and 1999, when this compilation was completed, no database existed with the latitudes and longitudes of the known mineral deposits and occurrences.

The west-central Srednogorie area, Bulgaria, is used here to illustrate how this compilation was conducted (figs. 22–24). On this composite image (fig. 22), northwest-trending linear features are interpreted as faults that are associated with green to pink changes in color. Elliptically shaped sedimentary basins range in color from pink to blue. In figure 23, the locations of the three largest porphyry copper deposits in Bulgaria are shown in relation to strike-slip faults transferred from the 1:1,000,000-scale map published by the Bulgarian Institute of Academy of Sciences (1973). The sense of movement on the faults (right lateral) is from Ivanov and others (2002). Open pits were used to confirm the locations of the three major porphyry copper deposits (Elatsite, Medet, and Assarel) (fig. 23). In addition, the locations of three smaller porphyry copper deposits (not shown) were determined using enlarged sections of the composite image, while three of the seven porphyry occurrences and three of the six epithermal vein deposits were tentatively identified on the satellite image by ground disturbance.

The geologic map shown in figure 24 contains much of the basic information that has been used for more than 25 years by U.S. Geological Survey (USGS) geologists to assess tracts of land for undiscovered mineral resources. This map includes information on the location of discovered deposits by type (for example, porphyry copper and polymetallic vein), the types of rocks associated with these mineral deposits (for example, coeval volcanic rocks and intrusive granitoids), and the more recent sedimentary cover that may obscure the rocks associated with the occurrence of undiscovered deposits (Singer, 1993). The addition of structural features (fig. 25)

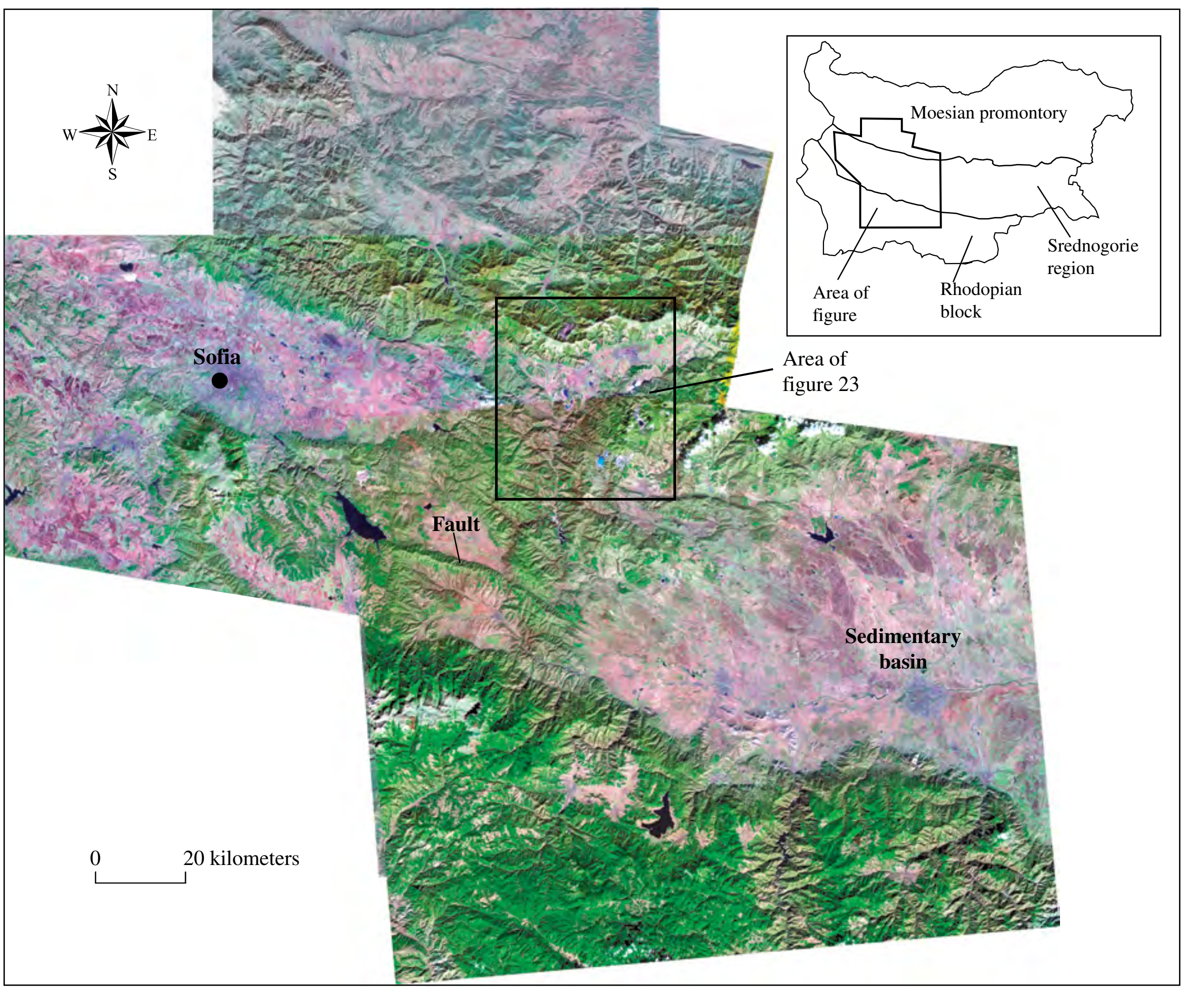

Figure 22. Landsat Thematic Mapper 7 composite image of the west-central Srednogorie region, Bulgaria. Spectral bands are red (band 7), green (band 4), and blue (band 2).

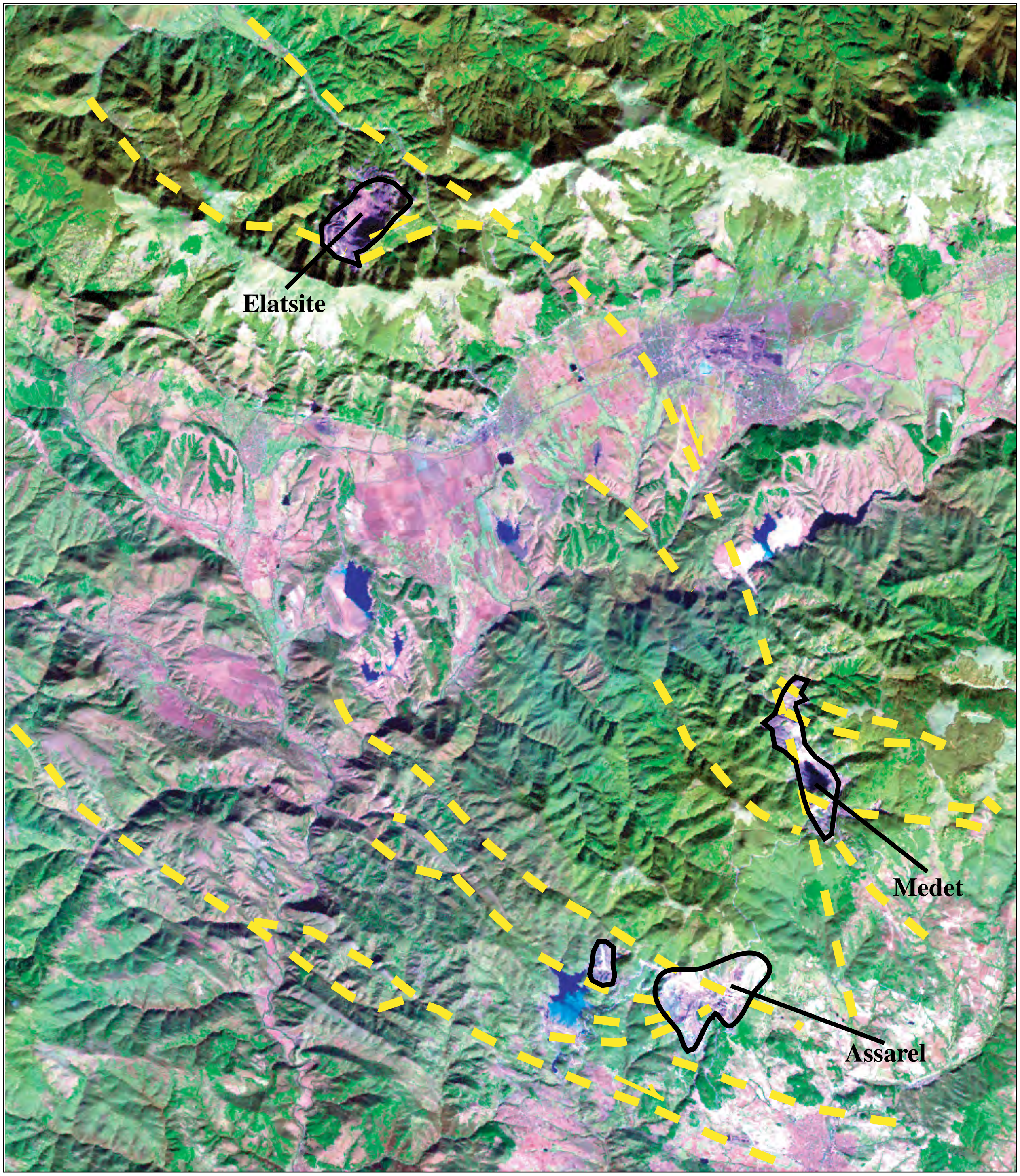

Figure 23. Satellite image showing the locations of the three largest porphyry copper deposits in Bulgaria (table 1) and their relation to the strike-slip faults in the region. Faults are transferred from the 1:1,000,000-scale geologic map of Bulgaria (Bulgarian Institute of Academy of Sciences, 1973). The sense of movement on the faults (right lateral) is from Ivanov and others (2002).

shows a close spatial association between the larger deposits and the inferred strike-slip fault duplexes (fig. 26). The Medet deposit (table 1) occurs in the northern corner of duplex 1a. The Elatsite deposit occurs in the northeastern corner of duplex 1, and the Assarel deposit occurs in the southeastern corner of duplex 1. Each of these porphyry copper deposits is located in or near granodiorite-quartz monzodiorite stocks in associated volcanics (Strashimirov and others, 2002). The Assarel deposit was emplaced at a shallow crustal level in a stock intruded into the superstructure of a volcano, whereas

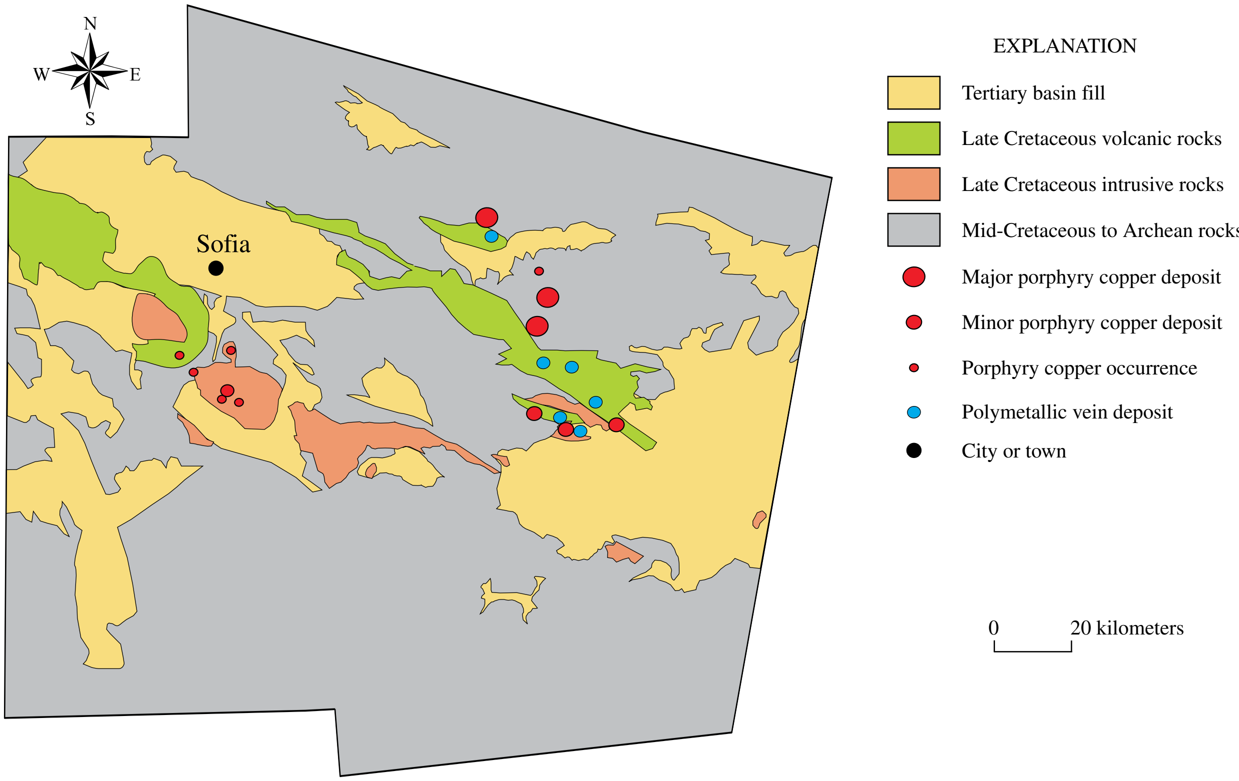

Figure 24. Geologic map showing rock types and known porphyry copper deposits in the west-central Srednogorie region, Bulgaria. Modified from Bulgarian Institute of Academy of Sciences (1973), Bogdanov (1983), Bayraktarov (1994), and Strashimirov and others (2002).

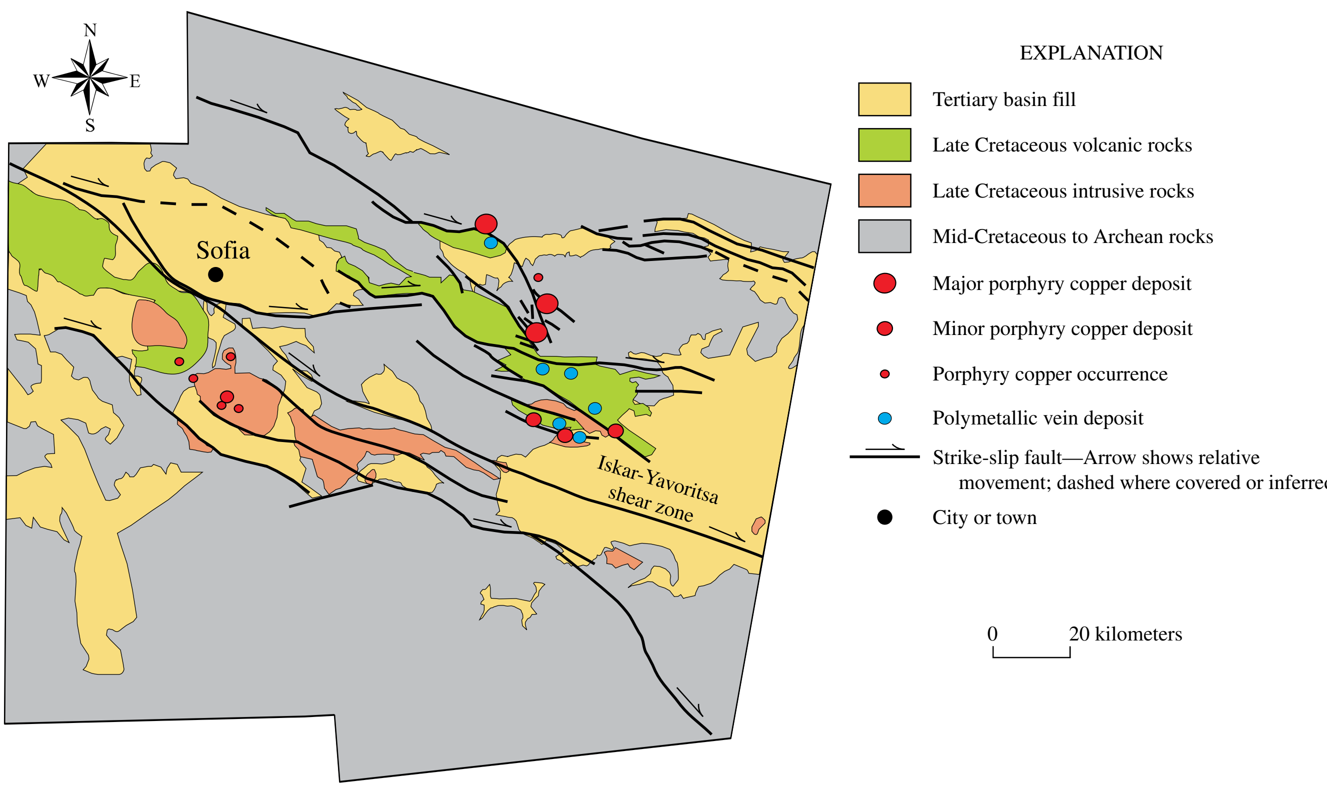

Figure 25. Geologic map showing rock types, known porphyry copper deposits, and strike-slip faults in the central Srednogorie region, Bulgaria. The major porphyry copper deposits are associated with small Late Cretaceous intrusive stocks (not shown) whereas most of the minor porphyry copper deposits and occurrences are associated with larger intrusive bodies (shown). Modified from Bulgarian Institute of Academy of Sciences (1973), Bogdanov (1983), Bayraktarov (1994), Ivanov and others (2002), and Strashimirov and others (2002).

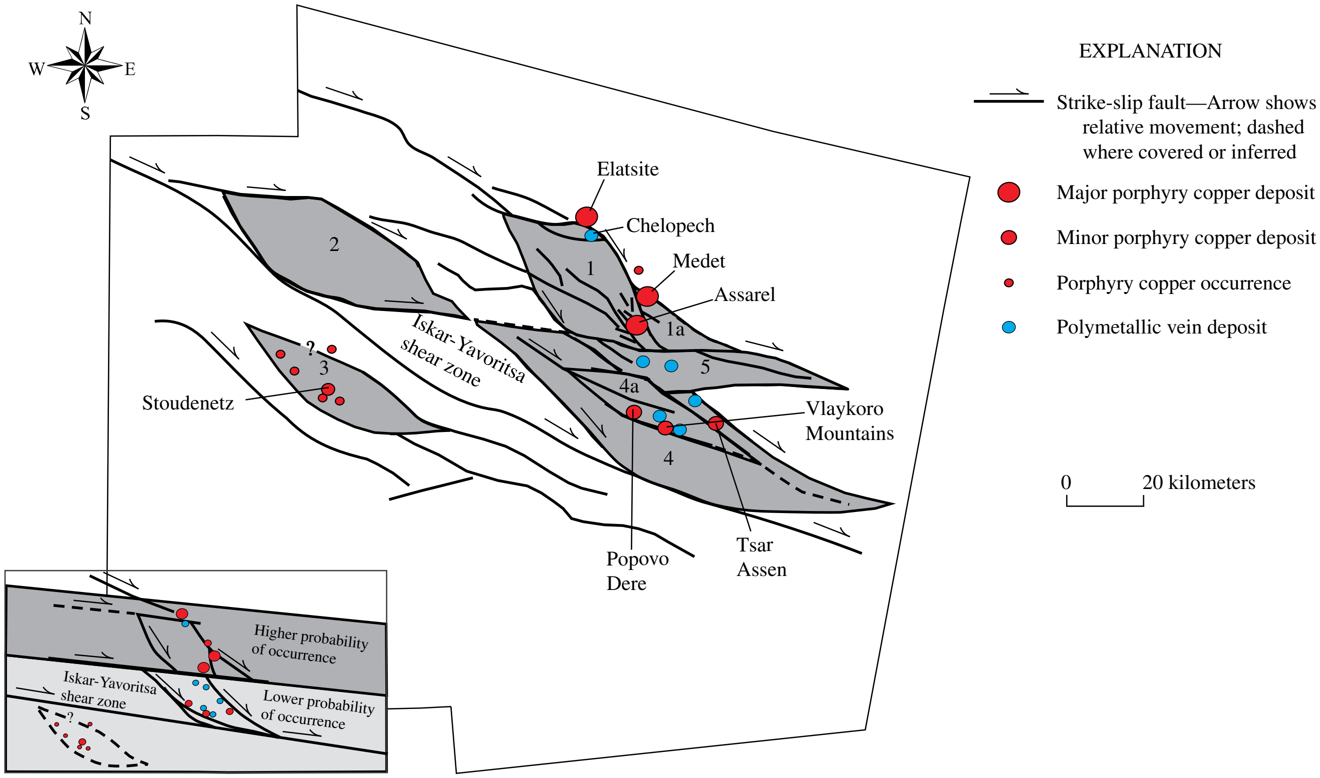

Figure 26. Map showing relations between porphyry copper deposits and their hosting strike-slip fault duplexes (shaded gray) in the west-central Srednogorie region, Bulgaria. Interpretation of additional faults based on geologic data from maps and satellite images. The numbered duplexes are discussed in text. Inset map shows interpretation of strike-slip duplex formation and the relative probabilities of occurrence of porphyry copper and polymetallic vein deposits relative to the location of the Iskar-Yavoritsa shear zone (see text for discussion).

the Medet and Elatsite deposits were emplaced at a somewhat deeper level (Strashimirov and others, 2002). These three deposits are located in zones of extensional fracturing.

The four minor porphyry copper deposits (Popovo Dere, Tsar Assen, Vlaykoro Mountains, and Stoudenetz) individually produced no more than 10 million metric tons of ore (Bogdanov, 1983; Ciobanu and others, 2002; Kouzmanov and others, 2002). Popovo Dere, Tsar Assen, and Vlaykoro Mountains occur along the edges of the strike-slip fault duplex labeled “4a,” which is within a larger duplex, labeled “4.” These minor deposits seem to occur on or near the boundary faults (lateral margins of the duplex structure shown in figure 9), where tensional fractures developed and produced sites favorable for the emplacement of porphyry stocks.

The Stoudenetz deposit and five porphyry copper occurrences are found in the proposed duplex structure labeled “3” (fig. 26). The faults that are shown on the 1:1,000,000-scale map in the vicinity of this proposed duplex are compatible with this interpretation (Bulgarian Institute of Academy of Sciences, 1973). The Stoudenetz deposit and the five occurrences have been tentatively identified as ground disturbances using the satellite images.

Relative Probability of Occurrence of Undiscovered Resources in Porphyry Copper and Polymetallic Vein Deposits

An important part in using the model in the assessment of undiscovered mineral resources is the determination of the levels of permissiveness of deposit occurrence in the region under consideration. For more than 25 years, information on rock type, deposit occurrence, and Tertiary sedimentary cover (fig. 24) has formed the basic data used by the USGS for the assessment of undiscovered mineral resources in tracts of land permissive for the occurrence of various types of mineral deposits (Singer, 1993). In addition, geophysical and exploration geochemical data have been used to identify the boundaries of land tracts permissive for undiscovered mineral deposits. According to the definition and methods developed by Singer (1993), the entire area shown in figure 24 would be classified as being permissive for the occurrence of undiscovered porphyry copper and polymetallic vein deposits because the tolerance probability level for permissiveness is set at 1 chance in 100,000 or P = 0.00001.

Using the tectonic deposit occurrence model presented here with additional tectonic analysis, the study area can be divided into subareas with different levels of probability for the occurrence of undiscovered porphyry copper and polymetallic vein deposits (fig. 26; Ivanov and others, 2002). Duplexes near the Iskar-Yavoritsa shear zone seem to contain only minor porphyry copper deposits and occurrences. The major porphyry copper deposits are associated with Late Cretaceous intrusive stocks (not shown) that are very small in areal extent (several square kilometers). The minor porphyry copper deposits and occurrences are associated with large plutons, for example, in the vicinity of duplex 3 (figs. 25, 26). Near the Iskar-Yavoritsa shear zone in the vicinity of duplex 3, a large Late Cretaceous granitoid body is exposed that has a long arching extension that terminates in the Iskar-Yavoritsa shear zone near the southern edge of duplex 4 (figs. 25, 26). This pattern of intrusion probably reflects emplacement under the influence of a devitoric stress field; that is, $\sigma_1 \neq \sigma_3$. The development of porphyry copper deposits requires a "stable" extensional stress field such as exists in the vicinity of the corners and edges of duplexes where tensional fracturing occurs (lower mean stress) and where $\sigma_1 = \sigma_3$. Under these conditions a porphyry stock repeatedly undergoes cycles of crystallization, fracturing of the encapsulating silica carapace, and emplacement of the ore minerals and silica and related gange minerals to form a major porphyry copper deposit (fig. 6). Such stable conditions generally are not maintained in the vicinity of a major shear zone.

The minor porphyry copper deposits (Popovo Dere, Tsar Assen, and Vlaykoro Mountains) located in duplex 4a (fig. 26) are associated with two northwest-trending granitoid bodies, suggestive of emplacement under devitoric stress. These deposits are interspersed with polymetallic vein deposits and concentrated along the edges of the duplex. If the model is correct, then the vein systems were deposited after the minor porphyry copper deposits. The porphyry copper deposits would have been deposited in an earlier extensional environment when the far-field stress was temporally nullified. This extensional environment would have been followed by an extensional-shear environment when the stress in the far field returned to being dominant. These polymetallic vein deposits may crosscut the porphyry deposits and (or) be located in an extensional-shear mesh between or outside the porphyry deposits.

Duplex 5 (fig. 26) is bounded on the north and south by strike-slip faults and probably contains a complex of smaller duplexes. Two polymetallic vein deposits occur in the middle of the duplex. No deposits or occurrences have been described from within duplex 2. This basin is bounded to the south by the Iskar-Yavoritsa shear zone making it doubtful that any significant porphyry copper or polymetallic vein deposits were formed. Even if deposits were formed, recent tectonic movement may have downdropped them into the basin, where they would be covered by sediments.

With the exception of the Chelopech polymetallic vein deposit (fig. 26), which is currently the largest gold-producing vein deposit in Europe, maps of the polymetallic vein deposits are undocumented in the published literature. The map for the vein system at Chelopech (Popov and Kovachev, 1996) suggests that the vein system is hosted in a local cone-sheet-radial dike subvariety (Park, 1983). This deposit is located near and somewhat inward in the duplex from the major Elatsite porphyry copper deposit (fig. 26).

Porphyry Copper and Associated Deposits in Serbia

Three major porphyry copper deposits have been discovered in the Timok magmatic zone, Serbia (fig. 27, table 1). Janković and others (1980) and Janković (1990) describe the Timok magmatic zone as a graben-syncline associated with a paleorift that has been filled by andesite, dacite, tuffs, and other volcaniclastic rocks, shale, and sandstone. Between 90 and 60 Ma these rocks were intruded by small calc-alkaline igneous stocks ranging in composition from gabbro to granodiorite, but most commonly monzonite (except for one, too small to show). The intrusions were emplaced during the reactivation of preexisting fractures.

The emplacement of the ore bodies at Majdanpek was controlled by a 0.3- to 0.6-km-wide north-trending positive flower structure (Janković and others, 1980; fig. 28). The outcropping ore bodies are continuous in this fracture zone for about 3 km and range in width from a maximum of 500 m to less than 100 m. The sense of displacement along the fracture zone is right lateral (fig. 28); faults in this zone have a down-to-the-east sense of displacement (Janković and Petkovic, 1982). There are several north-trending, nearly vertical faults in areas to the east and west of the Majdanpek deposit (Starostin, 1970; Janković and others, 1980; Janković and Petkovic, 1982).

Janković and Petkovic (1982) report that the individual porphyry copper ore bodies in the Majdanpek deposit are located in domes related to intrusions with the ore in apical parts of the intrusions or in arches above the intrusions. Starostin (1970) reports that the andesite in the ore zone is intensely brecciated and, locally, is sheared and hydrothermally altered. The greatest concentration of copper ore minerals occurs in the quartz-rich cores (fig. 28).

Closer examination of the ore bodies that comprise the Majdanpek deposit (fig. 28) suggests that the bodies have been emplaced in a positive flower structure (figs. 3, 10) within the PDZ of a master strike-slip fault. Stress on this master fault system appears to have been relayed across the northern part of the Timok magmatic zone (duplex) to an inferred strike-slip fault near the center of the duplex (fig. 29), thereby creating an extensional duplex. Figure 28 shows the location of Late Cretaceous andesite in which highly silicified bodies, referred to as "quartz-rich cores" occur. These "quartz-rich cores," which have the highest copper grades, are the location of the containment vessels where porphyry copper mineralization occurred (fig. 6).

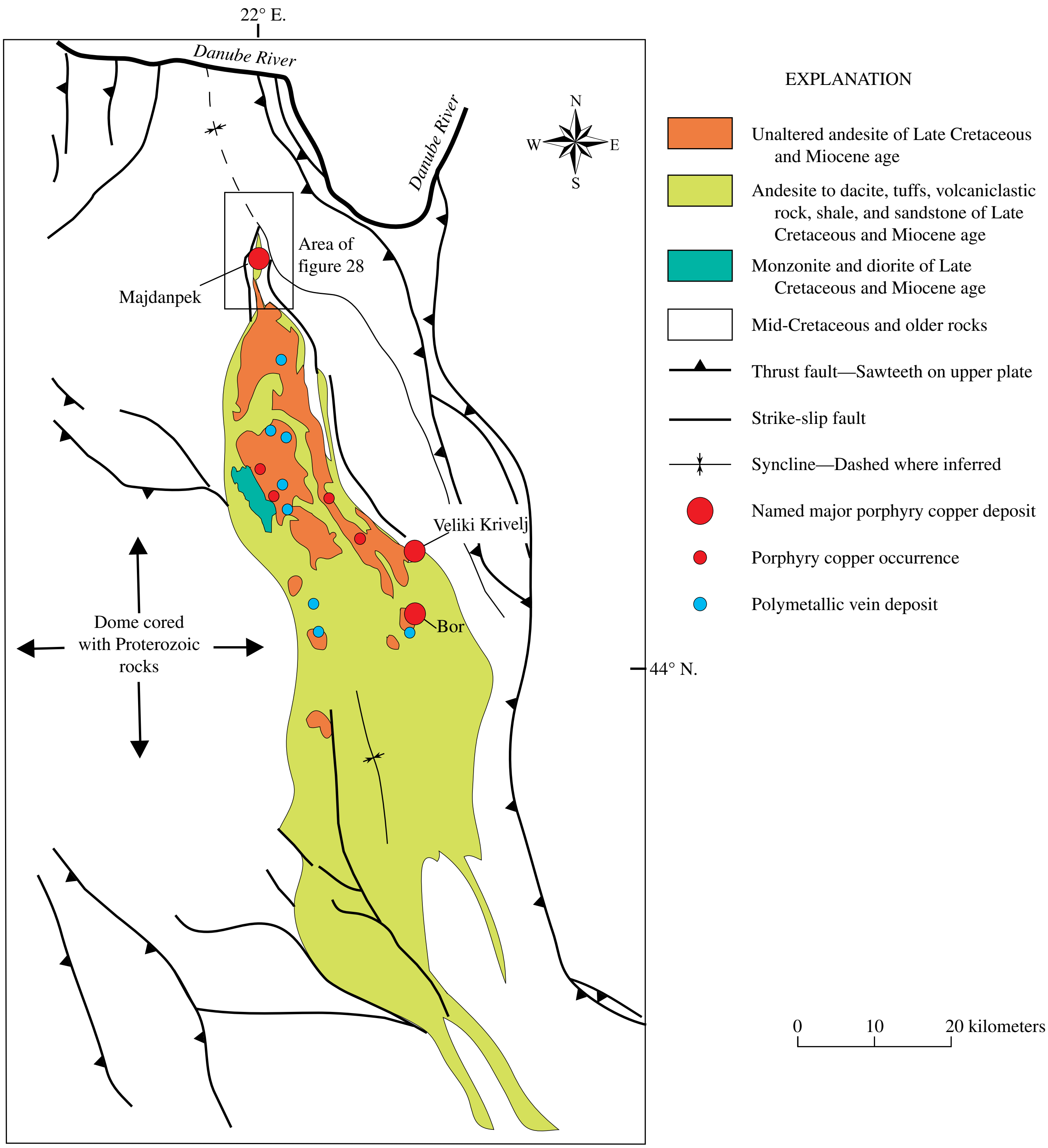

Figure 27. Porphyry copper deposits in the Timok magmatic zone (a strike-slip fault duplex) in Serbia. See figure 18 for location. Modified from Yugoslavia Federal Geological Institute (1970), Janković (1990), and Karamata and others (1997). Porphyry copper and vein deposit locations from Kozelj and Jelenkovic (2001).

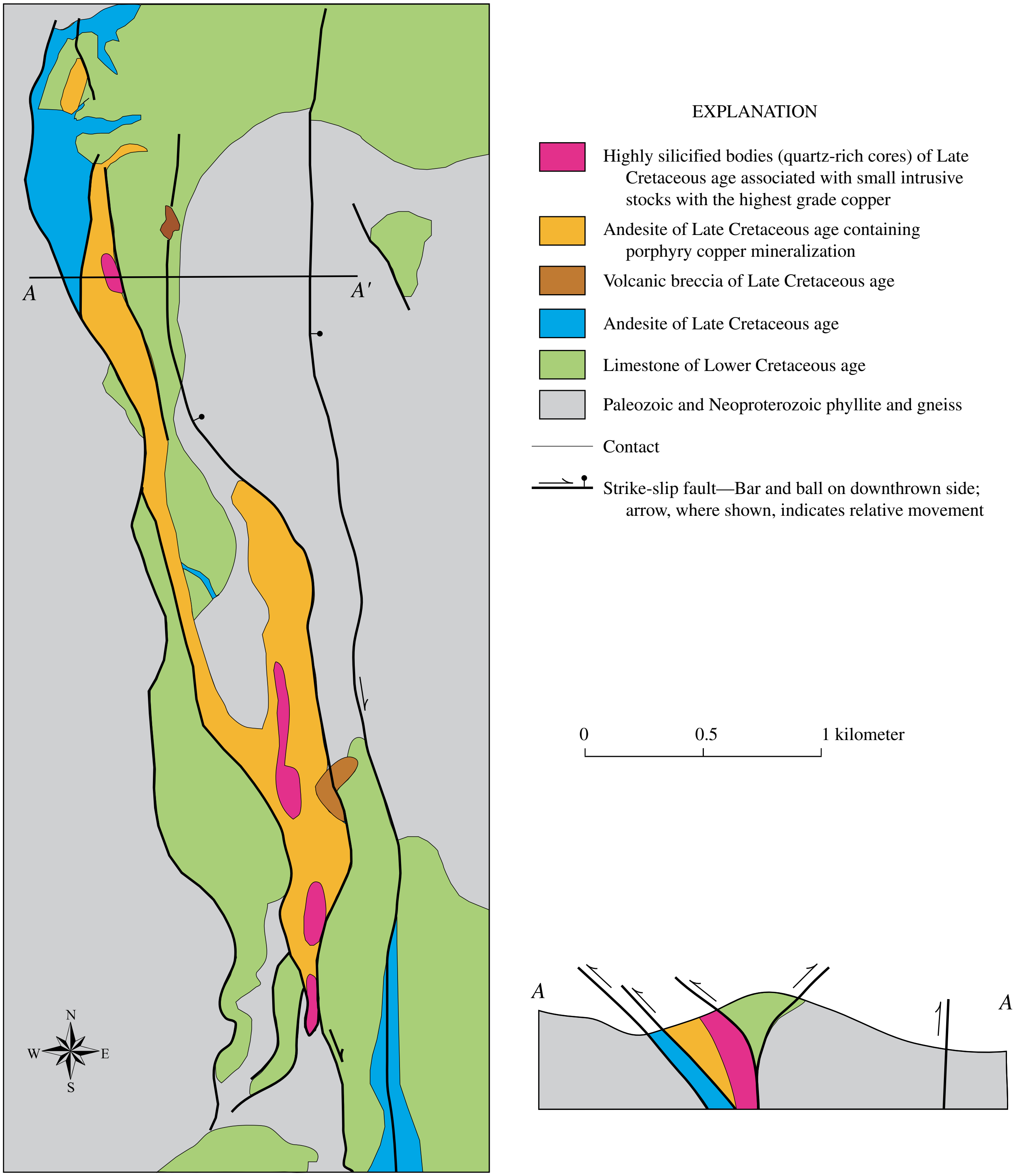

Figure 28. Map and schematic cross section illustrating a positive flower structure of the Majdanpek porphyry copper deposit. Compiled and modified from Starostin (1970) and Janković and others (1980).

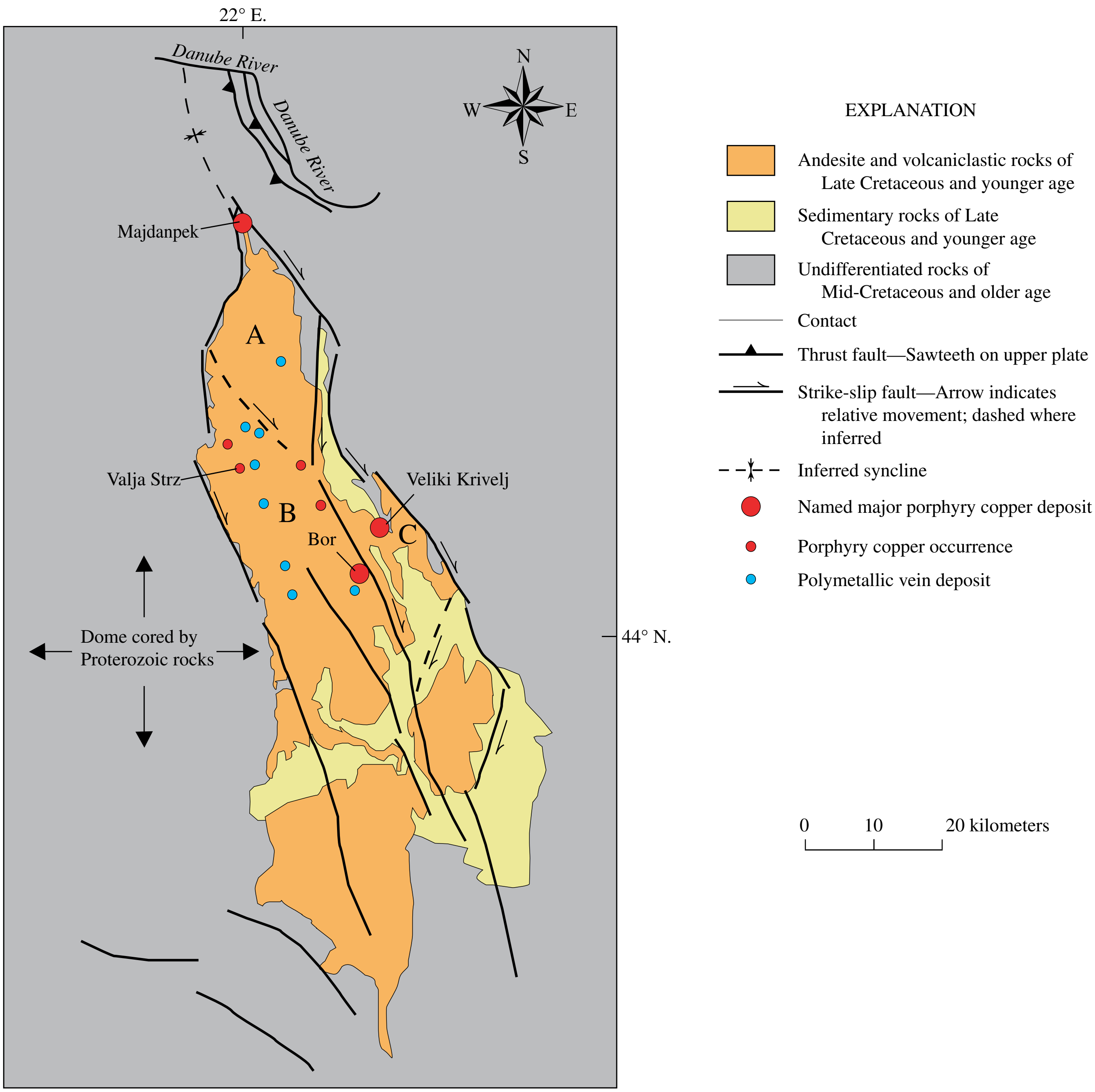

Figure 29. Tectonic map of the Timok magmatic zone (strike-slip fault duplex modified from Milovanovic, 1968), Serbia. Mapped rock units differ from those shown in figure 27 by the delineation of the Tertiary sediments and by not identifying the unaltered andesite. This map is used here because it emphasizes the structural geology of the duplex. Areas of the duplex designated by the letters A, B, and C (see text for discussion).

From the discussion above we conclude that the Timok magmatic zone is an extensional strike-slip duplex with a right-lateral, right-step sense of movement (figs. 27, 28). Note that two of the three major porphyry copper deposits are located along the eastern side of the duplex, while the four porphyry copper occurrences are located toward either side of the duplex (fig. 27). In contrast, the polymetallic vein deposits appear concentrated in the interior of the duplex. This configuration is consistent with the tectonic deposit occurrence model as described here (figs. 2–16).

The pattern of the faults in the duplex is best shown on a map by Milovanovic (1968), to which has been added a few additional faults proposed here by the author (fig. 29). The resulting duplex is composite in character with successive segments interpreted to have developed in a southern and possibly southwestern direction as stress was successively transferred from the series of strike-slip faults (see figures 27, 29). The initial opening of the Timok duplex was in the trough of a syncline where the rocks in the axial region had been weakened during previous regional deformation (figs. 27, 29).

The initial extension in the Timok fault duplex was in the small duplex in its northern part (area A in figure 29). The master fault on the southwestern margin of this duplex has been inferred by the author. The next duplexes to form may have been near the Bor and Veliki Krivelj porphyry deposits (areas B and C, respectively, in figure 29), although the order and timing of the development of these individual duplexes is not known. The Majdanpek deposit has been dated at 90±4 Ma, the Bor deposit at 79±4 Ma, and the Veliki Krivelj deposit at 76±6 Ma (Ciobanu and others, 2002). These age dates support the idea that the duplex opened and magma ascended in at least two stages progressing toward the south. The porphyry copper occurrence at Valja Strz on the western side of the Timok duplex has been dated at 78±4 Ma.

Porphyry Copper in the Banat Region, Romania

Porphyry copper and associated polymetallic vein deposits in the Banat region, Romania, are, for the most part, in a narrow, north-trending corridor on the western edge of the Getic nappe near or at its contact with the Supragetic nappe (fig. 30). The Getic nappe consists of Permian to Upper Cretaceous rocks that contain a substantial amount of limestone. This nappe is one of at least five nappes that were emplaced during the Early to Late Cretaceous (Vardar subduction) and were subsequently deformed by steeply dipping, right-lateral strike-slip faults during the Late Cretaceous and Paleocene (Ratschbacher and others, 1993; Willingshofer, 2000). The porphyry copper and polymetallic vein deposits are associated with small stocks and dikes of granitoid rocks of Late Cretaceous to Paleocene age (fig. 30). The limestone wall rock has been altered to discontinuous pods of skarn along the edge of the north-trending Getic nappe. The four largest pods are elongate in a north-south direction and are up to 8 km long and 1 to 2 km wide. The Moldova Nouă porphyry copper deposit is in the southern part of the southernmost skarn body (fig. 31*A*), and it is the only major porphyry copper deposit in the Banat region (fig. 30).

Gravitational Collapse and Escape Tectonics

These skarn bodies have map patterns consistent with extensional duplexes showing a left-lateral sense of shear (figs. 30, 31*A*). However, right sense of shear on Late Cretaceous to Paleocene faults in the Banat area was reported by Ratschbacher and others (1993), Schmid and others (1998), and Willingshofer (2000). This right sense of shear is consistent with the overall sense of shear during the closure of the Vardar Ocean in Bulgaria and Serbia, as discussed earlier (Burchfiel, 1980; Janković and others, 1980; Ivanov and others, 2002; Popov, 1987).

If the dominant sense of shear were right lateral during Late Cretaceous orogenic compression in the Srednogorie-Timok region, why does it appear to be left lateral in the Banat region? These relations may have resulted from the gravitational collapse of the nappe pile combined with tectonic escape (Dewey, 1988; Ratschbacher and others, 1989; Malavieille, 1993; Willingshofer, 2000).

Gravitational collapse initiates in local areas of the nappe pile when it becomes unstable because of its thickness and high relief. In these areas, collapse begins with local extension and the formation of low-angle normal faults. This extension begins while the nappes are being emplaced (Malavieille, 1993). During later stages of orogenesis, extensional stresses affect the entire orogen through strike-slip faulting and are associated with orogen-parallel extension.

During the process of orogen-parallel extension, blocks of continental crust may move laterally away from an orogen through the process of tectonic escape as oceans (such as the Vardar Ocean, shown in figure 20) are consumed. This process is well documented for collisional orogens such as the Alps and the Carpathians in Europe and the Himalayas in Asia (Royden and others, 1983; Dewey, 1988; Horváth, 1988; Tapponnier and others, 1982, 1986). During the process of tectonic escape the reversal of movement on strike-slip faults has been proposed, modeled, and verified in the field (Tapponnier and others, 1982, 1986; Ratschbacher and others, 1989; Peresson and Decker, 1997; Matenco and Schmid, 1999).

Perhaps the most complete analysis of the reversal of motion on strike-slip faults applies to the tectonic escape of the eastern Alps into the Pannonian region (Peresson and Decker, 1997). The gravitational collapse of the Alpine nappe pile and the resultant tectonic escape of the eastern Alps resulted from the collision between the Apulian/African and European plates during the early Eocene (55 Ma) to the early Miocene (17 Ma). During the middle Miocene, the sense of shear was reversed on several of the strike-slip faults that allowed tectonic escape of the eastern Alps. During the Eocene and early Miocene, the movement on these faults was

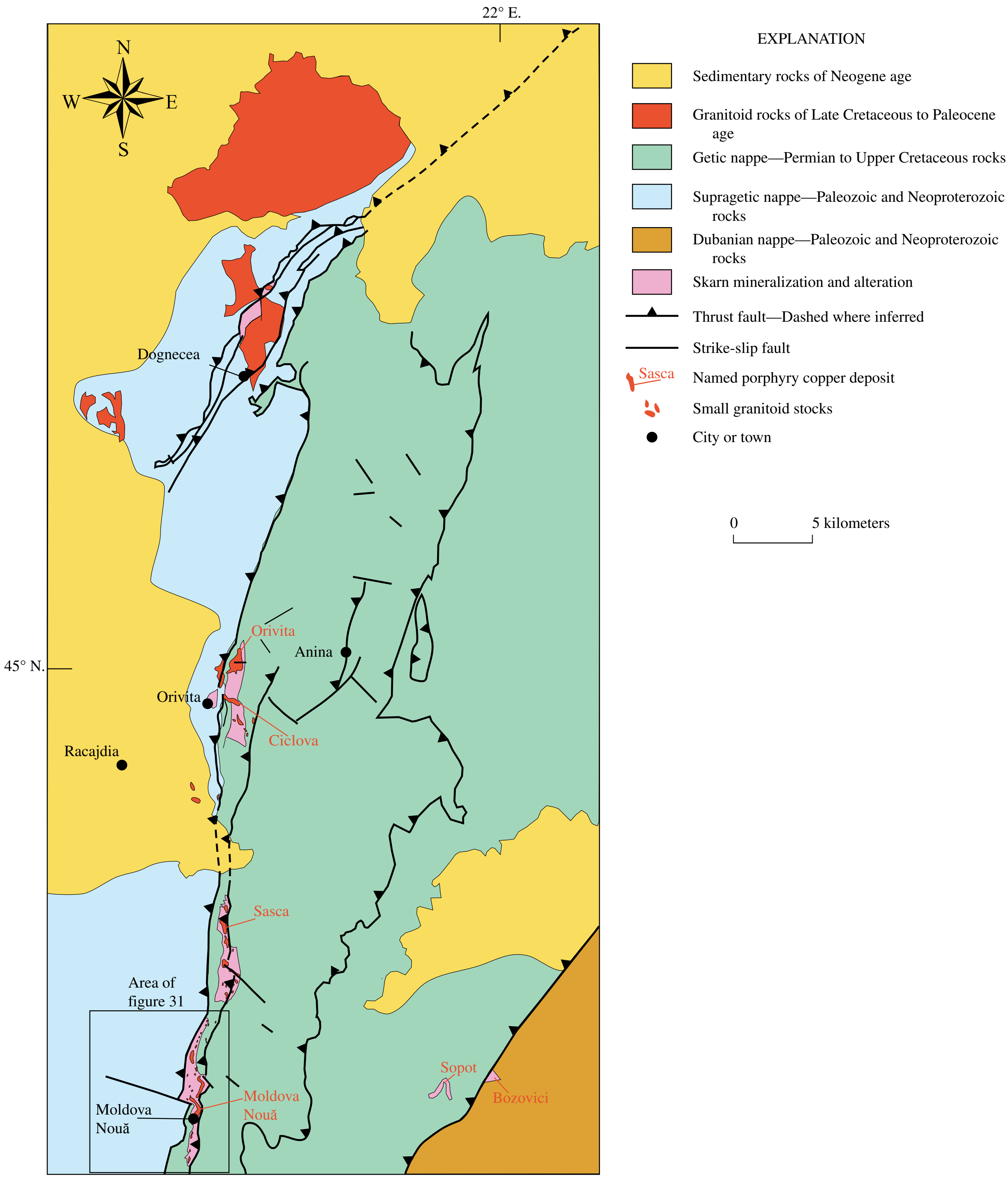

Figure 30. Geologic map of the Banat region, Romania. Modified from Codarcea (1967), Codarcea and Dimitrescu (1967), Codarcea and Răileanu (1968), Nastaseanu and Maier (1972), Maier and others (1973), and Nastaseanu and others (1975). See figure 18 for location.

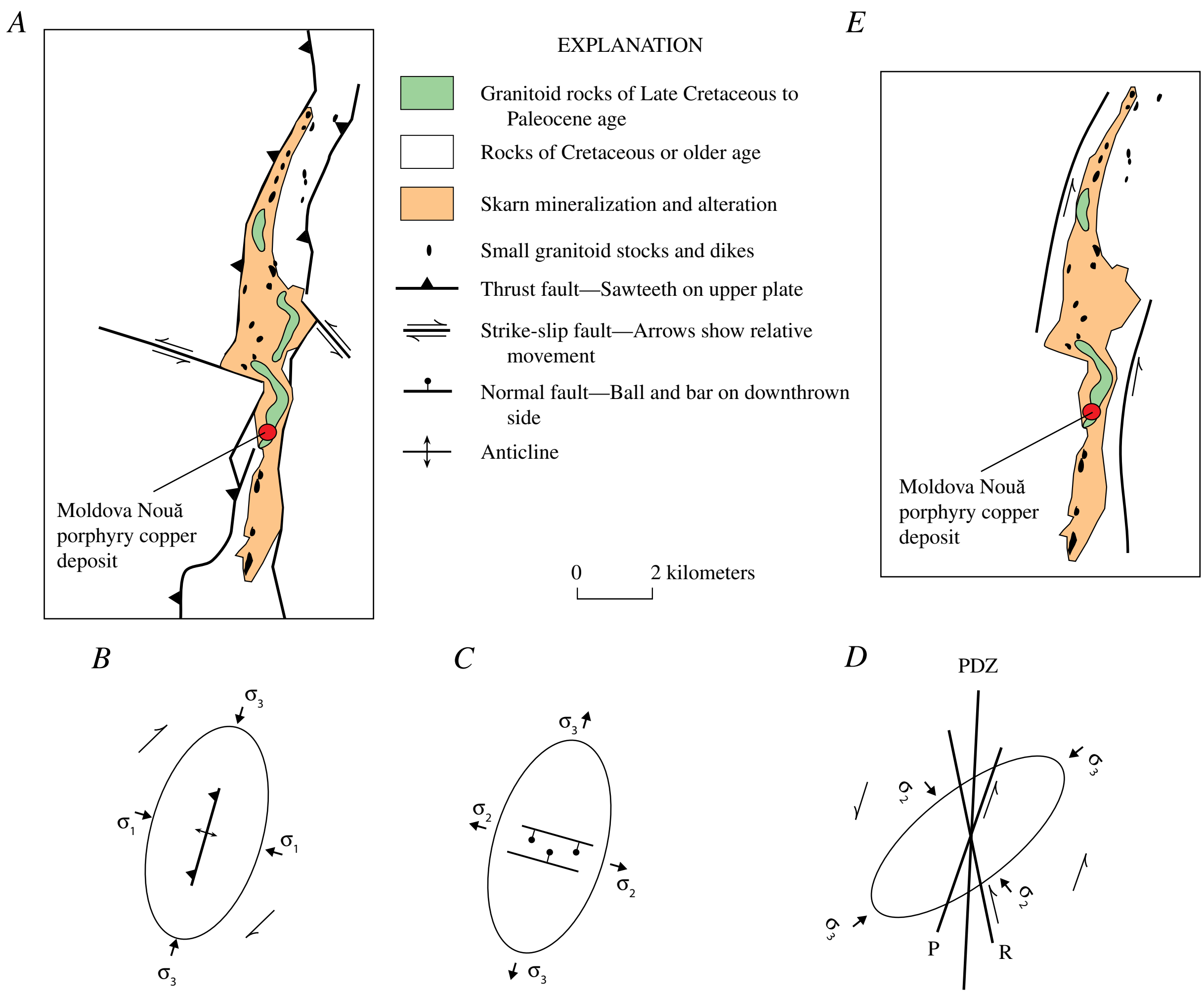

Figure 31. Tectonic elements in the area of the Moldova Nouă copper deposit in the Banat region, Romania. Modified from Nastaseanu and Maier (1972). See figure 30 for location. σ_1, maximum principal stress; σ_2, intermediate principal stress; σ_3, minimum principal stress; PDZ, principal deformation zone; R, synthetic shear fracture; P, antithetic shear fracture. *A*, Map view of the duplex hosting the Moldova Nouă porphyry copper deposit. *B*, Stress-strain ellipsoid showing the sense of thrusting and folding during Upper Cretaceous transpression. *C*, Stress-strain ellipsoid showing the sense of principal extension during orogenic collapse. *D*, Stress-strain ellipsoid showing reversal of the sense of shear from right lateral to left lateral as a consequence of orogenic collapse. *E*, Interpretation of the Moldova Nouă duplex as a left-lateral extensional duplex.

right lateral; during the middle Miocene, the movement on these faults was left lateral. Ratschbacher and others (1989) postulated that this reversal of movement sense resulted from the gravitational collapse of the Alpine nappe pile.

Near the boundary between the Getic and the Supragetic nappes in the Banat region, Romania (fig. 30), the author interprets the map patterns associated with the skarn bodies, granitoid stocks, and porphyry copper deposits to be the result of a left-lateral sense of shear (fig. 31*A*). Intrusion of the granitoid stocks and emplacement of the porphyry copper deposit and skarn bodies occurred after the reversal of the sense of shear from a right-lateral sense during the main tectonic compression to a left-lateral sense during tectonic escape. During this reversal, the thrust planes between the pairs of the Getic, the Supragetic, and the other nappes rotated from shallowly dipping thrusts to steeply dipping strike-slip faults (see cross sections in Codarcea, 1967). Stress-strain ellipsoids can be used to portray the sense of shear during orogenic transpression (fig. 31*B*), orogenic collapse and orogen-parallel extension (fig. 31*C*), and reversal of the sense of shear (fig. 31*D*). Emplacement of the porphyry stocks and the mineralization occurred during a left sense of shear (fig. 31*E*). The two northwest-trending, right-lateral faults are relics from the original right-lateral system. These relic faults become favored locations (anisotropies) for the later left-lateral fault system.

The nature of the extensional duplexes and associated skarn and porphyry copper mineralization in the Banat region differs from that in the Srednogorie and Timok regions. In the

Banat region, the areal extent of the duplexes is a small fraction of that in the Srednogorie and Timok regions, and no sedimentary basins formed. The entire volume of rock that was extended is altered with skarn alteration which, in turn, hosts the porphyry stocks and porphyry copper mineralization. For the purpose of assessing undiscovered deposits, the Late Cretaceous ages of the host rock, deformation, porphyry stocks and mineralization, and position in orogen suggests that Banat mineralization should be associated with a tectonic regime, intermediate between the external and internal tectonic basins of Willingshofer (2000).

Middle Miocene Porphyry Copper and Polymetallic Vein Deposits in Romania and Slovakia

Apuseni Mountains, Romania

The opening of extensional duplexes (basins) and the emplacement of andesitic volcanic and associated granitoid rocks in the Apuseni Mountains, Romania, was coupled with the eastward tectonic escape of and extension within the Carpathian-Pannonian region during the Miocene (Royden and others, 1983; fig. 32). From 17 to 15 Ma, extension and basin development prevailed in the region (fig. 33; Fodor and others, 1999). The opening of the Brad-Sacaramb basin, and presumably the Zarand basin to the northwest (fig. 33), was facilitated by the preexisting anisotropy that had been introduced into this region by thrusting during the Jurassic. This anisotropy not only determined the configurations of the basins but also controlled the positioning of the fault duplexes within the basins when the far-field stress regime evolved from local rift-like tectonics during Karpatian-earliest Badenian time (fig. 33) to strike-slip tectonics during late Badenian-Sarmatian time (fig. 34). Fodor and others (1999) initially interpreted the sense of motion during this latter stage as left lateral. Newly acquired field data suggests, however, that the sense of shear of the faults associated with the emplacement of the middle Miocene porphyry copper and polymetallic vein deposits in the Apuseni Mountains is not left lateral, but instead right lateral (Gary O'Connor, Gabriel Resources Ltd., written commun., 2004). The fault duplexes important for creating the local environment for emplacement of porphyry copper and polymetallic

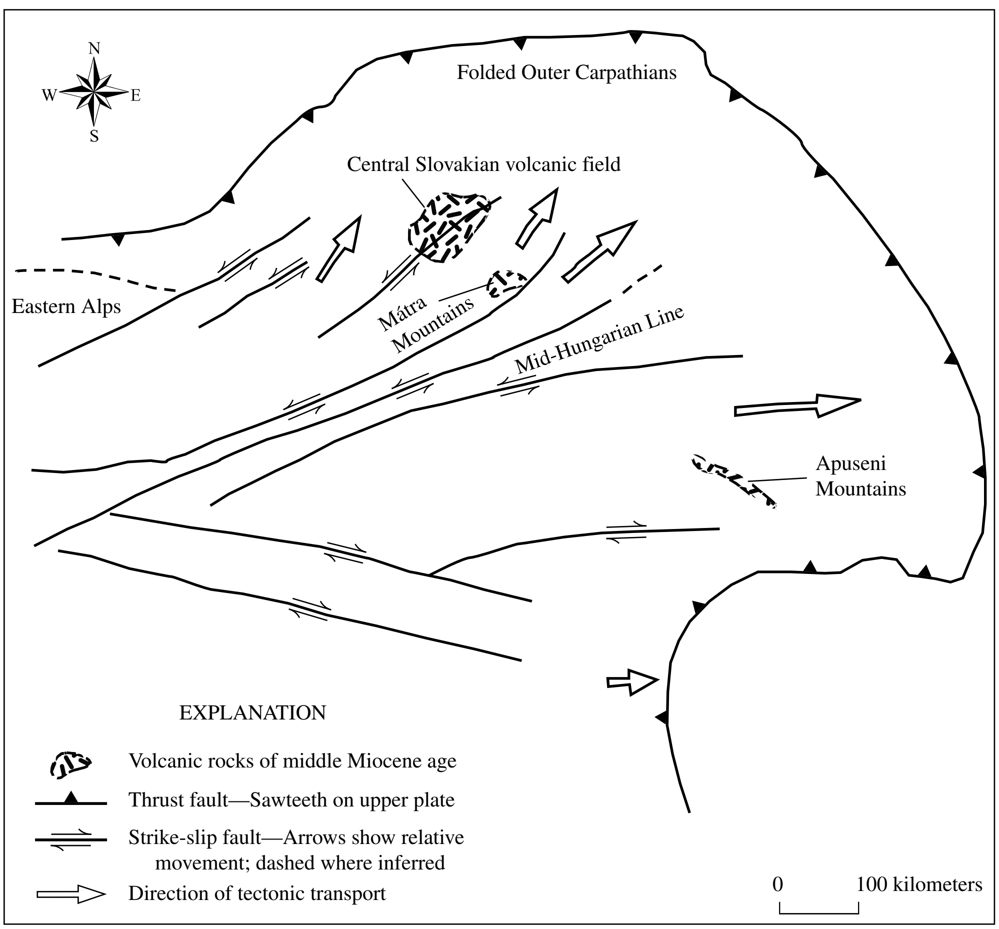

Figure 32. Schematic diagram showing tectonic transport direction in the Carpathian-Pannonian region during the middle Miocene and location of middle Miocene volcanic rocks. Modified from Csontos and others (1992) and Rumpler and Horváth (1988).

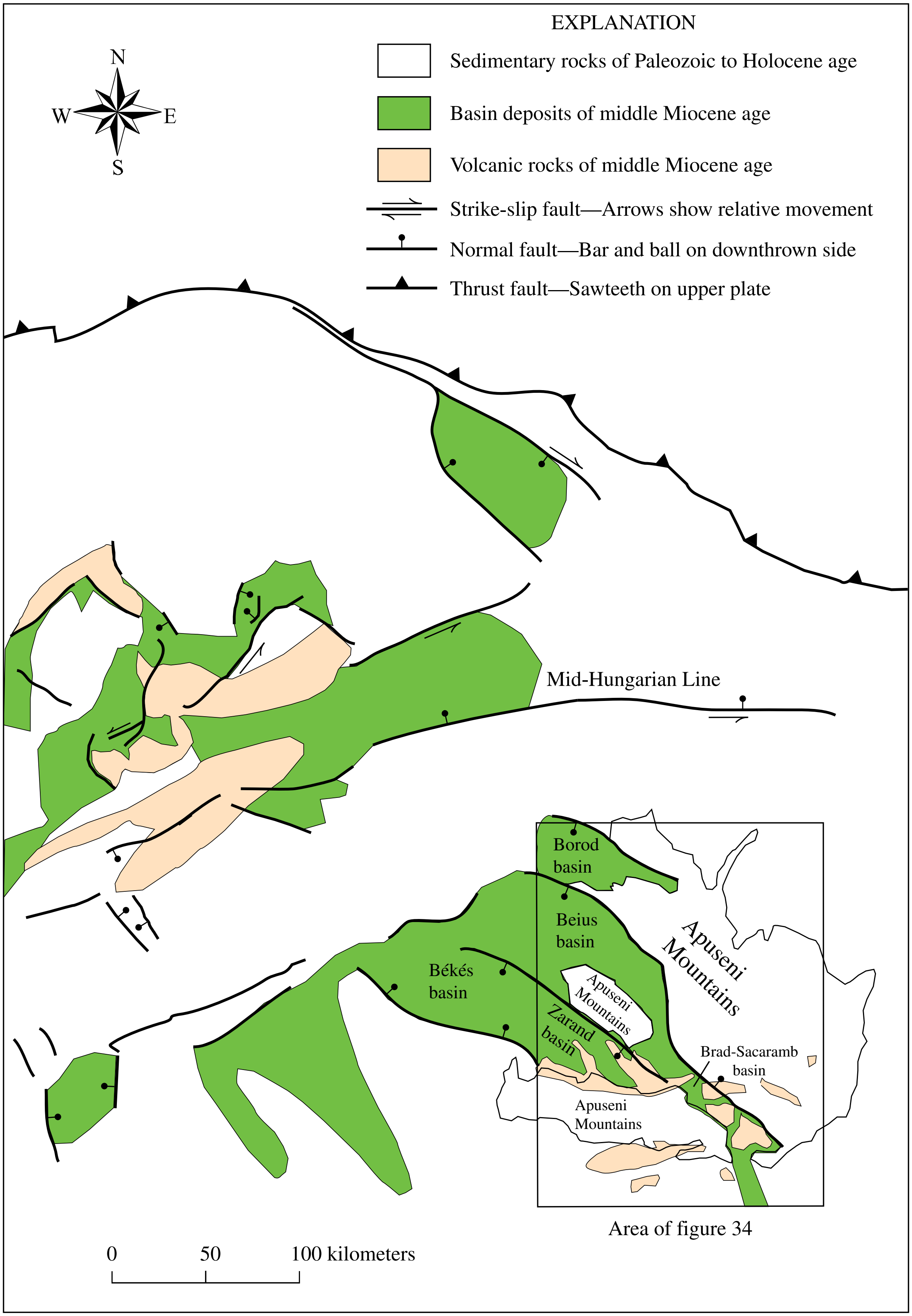

Figure 33. Map showing extension during the Karpatian-earliest Badenian (17–15 Ma). Modified from Fodor and others (1999).

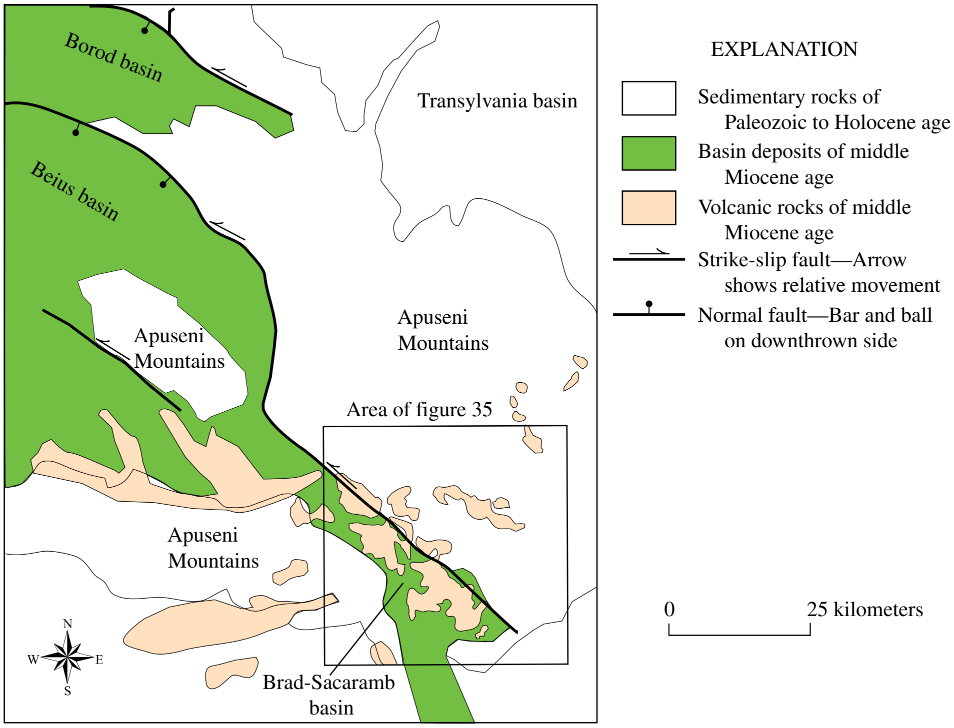

Figure 34. Strike-slip faults formed in the study area during the late Badenian-Sarmatian (14–11 Ma). Modified from Ghițulescu and Socolescu (1941) and Fodor and others (1999).

vein deposits can be created by either sense of stress. The sense of shear used in the interpretation presented above as taken from Fodor and others (1999) only needs to be reversed. The general conclusions about the occurrence of these types of deposits in various positions in the duplexes will be the same. The sense of shear is not the important first order effect in the emplacement; instead it is the creation of the duplex structure itself.

During the late Badenian-Sarmatian, intrusive and related volcanic rocks were emplaced in the Brad-Sacaramb and Zlatna basins (fig. 35). Fifteen porphyry copper deposits and occurrences have been mapped in these basins and adjacent areas, and at least ten polymetallic vein deposits were emplaced in extensional-shear mesh structures. The Sacaramb-Hondol duplex (fig. 36) had a rotational component and contains several smaller embedded duplexes. Therefore, it is more complex than the other duplexes so far described in this paper. This duplex contains the Bolcana-Troija and the Voia porphyry copper deposits located near its margins (fig. 36). Several of the embedded duplexes also contain polymetallic vein deposits. Maps and cross sections of the Sacaramb and Hondol polymetallic vein deposits show that the veins are in meshes related to extensional and shear faults (Berbeleac and others, 1995b), while the Hanes deposit (not shown) is in a negative flower structure (Drew and others, 1999a). Many of the veins have produced large tonnages of high-grade zinc, copper, lead, and gold ore.

Central Slovakian Volcanic Field

In the central Slovakian volcanic field, the spatial and kindred association between copper porphyry and polymetallic vein deposits is well defined (fig. 37; see figure 1 for location). The Banksa Stiavnica graben, an extensional basin (duplex), located to the west of the town of Banksa Stiavnica contains polymetallic vein deposits and three porphyry copper deposits. The main production has been from the polymetallic vein system inside the extensional basin—70,000 metric tons (t) of Zn, 55,000 t of Pb, 8,000 t of Cu, 4,000 t of Ag, and 80 t of Au (Lexa and others, 1999). The Kremnica graben, the extensional basin (duplex) to the north of the Banksa Stiavnica graben (fig. 37), also has been productive—208 t of Ag and 46 t of Au. It contains reserves of 230 t of Ag and 30 t of Au (Lexa and others, 1999).

Within the Banksa Stiavnica graben, three porphyry copper deposits are located near the margins of the duplex and close to three of its corners. The productive and nonproductive veins have the meshlike form predicted by the extensional-shear model (fig. 12). Equally important, the porphyry copper deposits that formed between 16.4 and 16.0 Ma are older than the polymetallic vein deposits that formed between 13.5 and 10.5 Ma; this timing is consistent with the tenets of the model for the porphyry copper-polymetallic vein deposit system.

Polymetallic veins also occur within an extensional-shear mesh in the Kremnica graben, to the west and northwest of

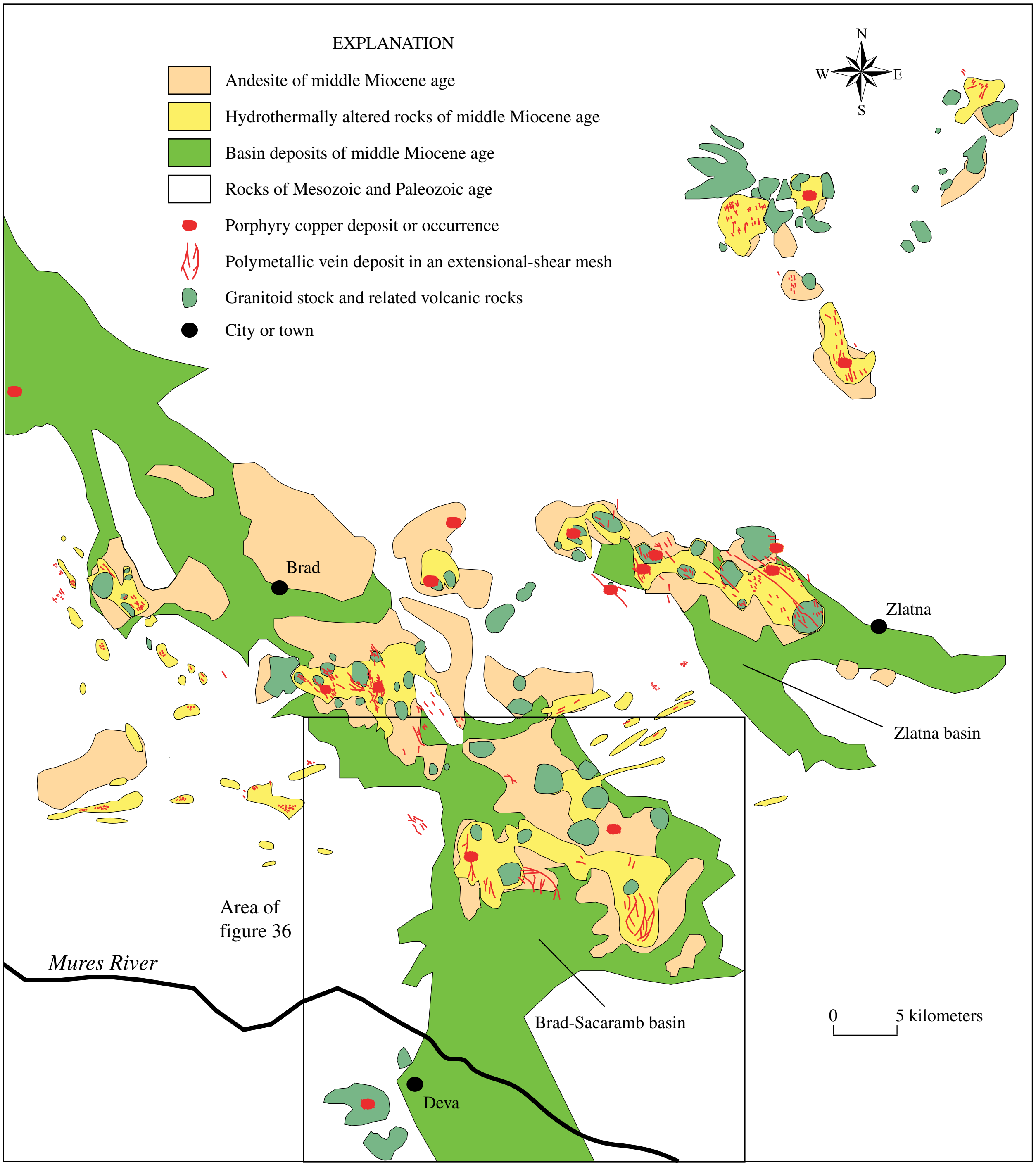

Figure 35. Map showing porphyry copper and polymetallic vein deposits, andesitic volcanic rocks, granitoid stocks, alteration, and Tertiary sediments in the Brad-Sacaramb and Zlatna basins, Apuseni Mountains, Romania. Modified from Ghițulescu and Socolescu (1941), Borcoş (1994), and Berbeleac and others (1995b). See figure 34 for location.

the town of Kremnica (fig. 37). This vein system has been localized in the corner of the graben where the mesh expands out into the basin. A slightly altered igneous stock containing low-grade sulfide minerals has been intersected in drill holes near these veins (Jaroslav Lexa, Geological Survey of Slovak Republic, oral commun., 2001). This weakly mineralized stock is the "porphyry" associated with the polymetallic veins. Note that the volume of metal deposited in the mesh is also small. To deposit large tonnages of high-grade ores in veins, a mesh must remain essentially closed, opening only occasionally during intermittent seismic activity to receive new hydrothermal fluid. The extensional-shear mesh func-

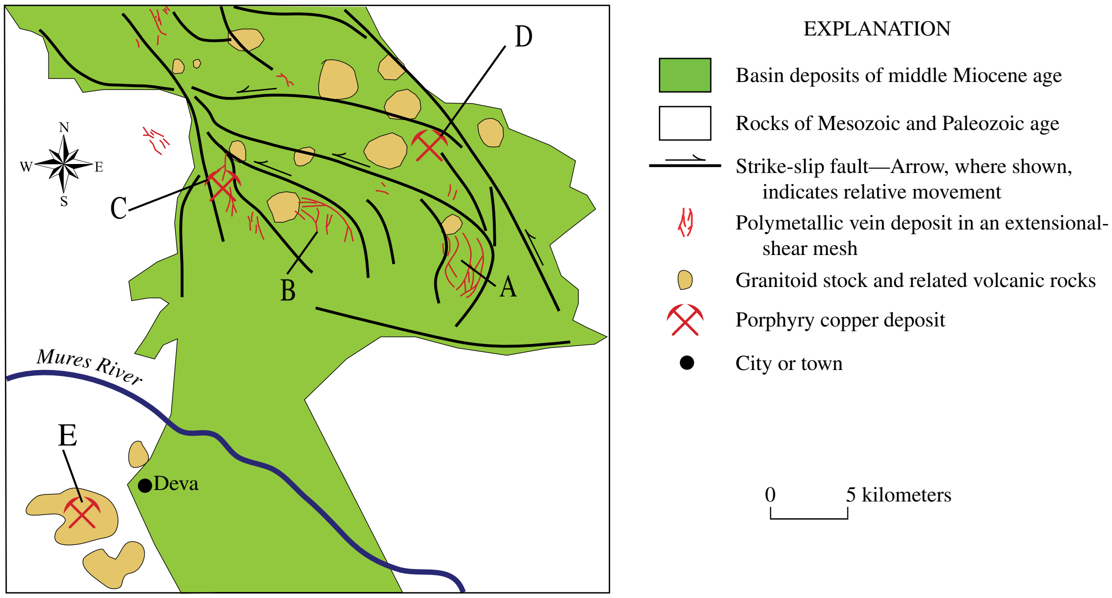

Figure 36. Porphyry copper and polymetallic vein deposits in the Sacaramb-Hondol duplex in the Apuseni Mountains, Romania. Deposits are Sacaramb (A), Hondol (B), Bolcana-Troija (C), Voia (D) , and Deva (E). Modified from Ghițulescu and Socolescu (1941) and Berbeleac and others (1995a,b). See figure 35 for location.

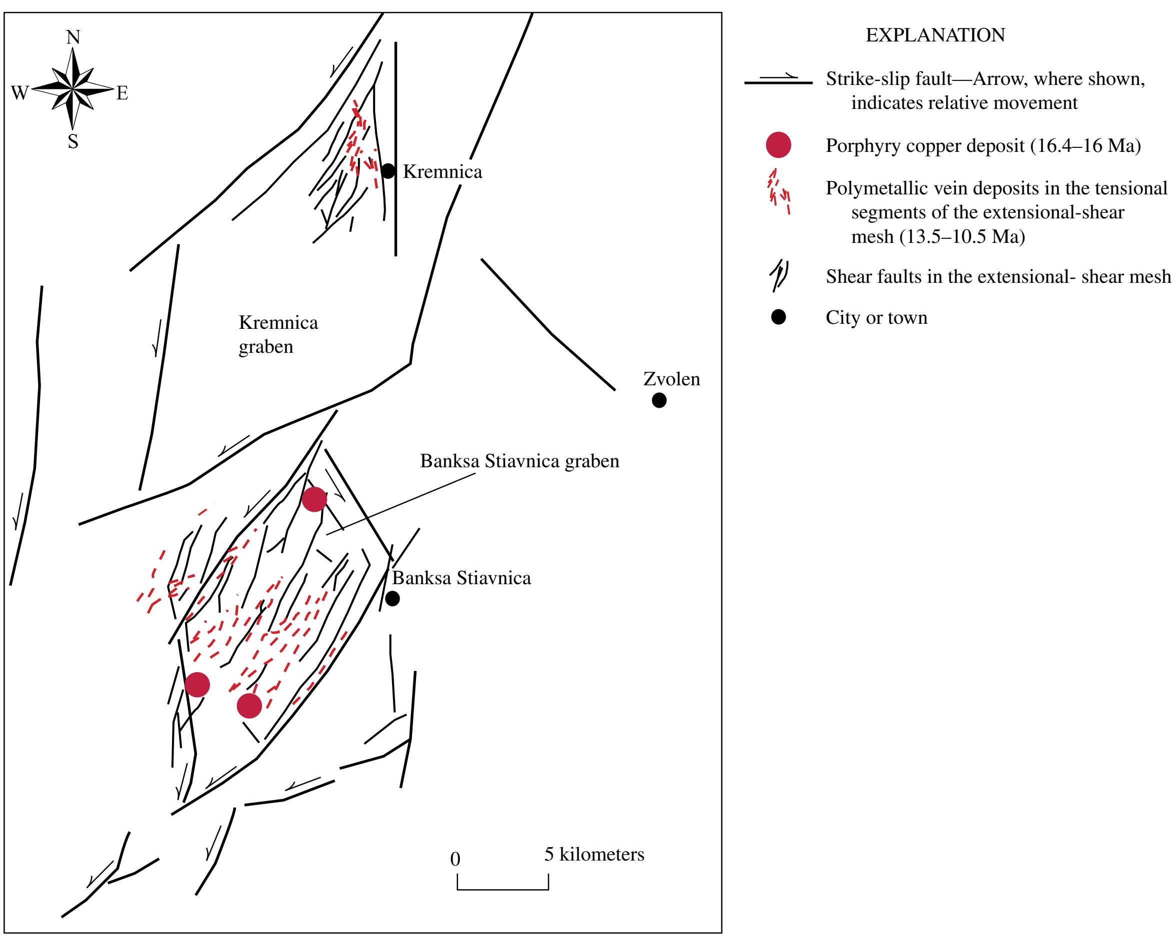

Figure 37. Map showing the pull-apart basins created by strike-slip faulting and the location of porphyry copper and polymetallic vein deposits in the central Slovakian volcanic field near Kremnica and Banksa Stiavnica, Slovakia. Modified from Marsina (1995) and Lexa and others (1999). See figure 1 for location.

tions by repeatedly opening and closing. This is documented by comparing the vein systems in the Banska Stiavnica and the Kremnica grabens. The mesh has opened outward into the basin in a fanlike manner in the Kremnica graben, whereas it is more closed in the Banksa Stiavnica graben (fig. 37).

Conclusions

A tectonic model useful for estimating the occurrence of undiscovered deposits in the porphyry copper-polymetallic vein family developed recently by Berger and Drew (1997), Drew and others (1999a), Drew and Berger (2001, 2002), and Drew (2003) has been expanded by using data associated with such deposits in central Europe.

The model expands the regions favorable for extensional and shear fracturing in strike-slip fault duplexes. Additionally, the new model can be used to isolate the potentially mineralized duplexes (internal extensional basins) from the many duplexes (external extensional basins) developed during orogenic compression and collapse and in other extensional tectonic regimes.

The model explains the occurrence of porphyry copper and polymetallic vein deposits in the Late Cretaceous Banat-Timok-Srednogorie orogen that extends for 1,500 km from western Romania across Serbia and central Bulgaria. The porphyry copper deposits discovered to date are located in the corners and along the edges of the duplexes, and the polymetallic vein deposits are located nearby and more internal in the duplexes from the porphyry deposits. Often the polymetallic veins crosscut the porphyry stockwork.

Elsewhere in central Europe, the expanded model explains the location of the Miocene-age porphyry copper and polymetallic vein deposits equally well. In the central Slovakian volcanic field, the porphyry deposits, which are located toward the corners of the duplexes, have ages of about 16 Ma, and the polymetallic veins, which have been deposited more centrally in the duplexes, are younger (13.5–10.5 Ma). In the Brad-Sacaramb basin, Apuseni Mountains, Romania, the porphyry copper and polymetallic vein deposits are also Miocene in age. Although the tectonic history of this region is more complex, the model can account for the distribution of deposits.

Newly acquired ASTRA satellite data will add an important source of information as to the location of various types of hydrothermal alteration, which when used in conjunction with the tectonic data, should substantially enhance the process of estimating the inventory of undiscovered resources.

Acknowledgments

The author wishes to thank A.P. Schultz, A.A. Drake, Jr., and K.J. Schulz for many constructive suggestions in their reviews of the manuscript; L.C. Rowan and J.C. Mars for providing many types of processed satellite images without which this work could not have been done; C.L. Ciobanu and N.J. Cook for providing otherwise unobtainable data on the geology and porphyry copper deposits in the Banat (Romania) and Timok (Serbia) areas; Irena Peycheva for data for the Srednogorie (Bulgaria) region; R.D. Hatcher for discussion of the reversal of movement on strike-slip faults; Ion Berbeleac for much useful discussion on the economic geology and for leading two field trips in the Baia Mare and Brad-Sacaramb areas of Romania; John Menzies, Radoslav Narkov, and Strashimir Strashimirov for providing the information used for the cover photograph; and B.R. Berger for a long and productive collegial association on the development of many of the ideas expanded upon here in this paper.

References Cited

Antonijević, I., Grubić, A., and Djordjević, M., 1974, The Upper Cretaceous paleorift in eastern Serbia, *in* Janković, Slobodan, ed., Metallogeny and concepts of the geotectonic development of Yugoslavia: Belgrade, University of Belgrade, p. 315–339.

Bally, A.W., and Oldow, J.S., 1985, Plate tectonics, structural styles, and the evolution of sedimentary basins (3d ed.): Tulsa, Okla., American Association of Petroleum Geologists Short Course, 238 p.

Bayraktarov, Ivan, 1994, Porphyry copper mineral types in western Srednogorie and Plana Mountains: Ore-forming processes and mineral deposits, v. 34, p. 3–18.

Berbeleac, Ion, Iliescu, Dan, Andrei, Justin, Ciuculescu, Ovidiu, and Ciuculescu, Rodica, 1995a, Relationships between alterations, porphyry copper-gold and base metal-gold hydrothermal vein mineralizations in Tertiary intrusions, Talagiu area, Zarand Mountains: Romanian Journal of Mineral Deposits, v. 76, p. 31–39.

Berbeleac, I., Popa, T., Ioan, M., Iliescu, D., and Costea, C., 1995b, Main characteristics of Neogene-volcanic-subvolcanic structures and hosted ore deposits in Metalliferi Mountains: Geologica Macedonica, v. 9, no. 1, p. 51–60.

Berger, B.R., and Drew, L.J., 1997, Role of strike-slip duplexes in localization of volcanoes, related intrusions, and epizonal ore deposits [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A359–A360.

Berger, B.R., Drew, L.J., and Singer, D.A., 1999, Quantifying mineral-deposit models for resource assessment: Geologica Hungarica, v. 24, p. 41–54.

Bergerat, Françoise, Martin, Pierre, and Dimov, Dimo, 1998, The Moesian Platform as a key for understanding the geodynamical evolution of the Carpatho-Balkan alpine system, *in* Crasquin-Soleau, Sylvie, and Barrier, Eric, eds., Stratigraphy and evolution of peri-Tethyan platforms: Mémoires du Muséum National d'Histoire Naturelle, v. 177 (Peri-Tethys Memoir 3), p. 129–150.

Berza, Tudor, Constantinescu, Emil, and Vlad, Şerban-Nicolae, 1998, Upper Cretaceous magmatic series and associated mineralisation in the Carpathian-Balkan orogen: Resource Geology, v. 48, no. 4, p. 291–306.

Bliss, J.D., and Cox, D.P., 1986, Grade and tonnage model for polymetallic veins, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 125–129.

Bogdanov, B.D., 1983, Porphyry-copper deposits of Bulgaria: International Geology Review, v. 25, no. 2, p. 178–188.

Borços, M., 1994, Volcanicity/metallogeny in the south Apuseni Mts (Metalliferi Mts), *in* Borços, M., and Vlad, S., eds., Plate tectonics and metallogeny in the east Carpathians and Apuseni Mts., June 7–19, 1994, Field trip guide (IGCP Project 356): [Bucharest] The Geological Institute of Romania, p. 32–43.

Bulgarian Institute of Academy of Sciences, 1973, Geologic map of Bulgaria: Bulgarian Institute of Academy of Sciences, sheet 24–25, scale 1:1,000,000.

Burchfiel, B.C., 1980, Eastern European alpine system and the Carpathian orocline as an example of collision tectonics, *in* Banks, M.R., and. Green, D.H., eds., Orthodoxy and creativity at the frontiers of earth sciences: Tectonophysics, v. 63, p. 31–61.

Burnham, C.W., 1979, Magmas and hydrothermal fluids, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits (2d ed.): New York, John Wiley & Sons, Inc., p. 71–136.

Carranza, E.J.M., and Hale, Martin, 2002, Where are porphyry copper deposits spatially localized? A case study in Benguet Province, Philippines: Natural Resources Research, v. 11, no. 1, p. 45–59.

Ciobanu, C.L., Cook, N.J., and Stein, Holly, 2002, Regional setting and geochronology of the Late Cretaceous Banatitic Magmatic and Metallogenetic Belt: Mineralium Deposita, v. 37, no. 6/7, p. 541–567.

Codarcea, Al., ed., 1967, Timişoara: Institutul Geologic, no. 24, sheet L–34–XXII, scale 1:200,000.

Codarcea, Al., and Dimitrescu, R., eds., 1967, Deva: Institutul Geologic, no. 25, sheet L–34–XXIII, scale 1:200,000.

Codarcea, Al., and Răileanu, Gr., eds., 1968, Resita: Institutul Geologic, no. 31, sheet L–34–XXVIII, scale 1:200,000.

Connolly, Peter, and Cosgrove, John, 1999, Prediction of fracture-induced permeability and fluid flow in the crust using experimental stress data: American Association of Petroleum Geologists Bulletin, v. 83, no. 5, p. 757–777.

Council for Mutual Economic Assistance, Postoiannaia Komissiia po Geologii, Delegatsiia SSSR, 1977, Map of mineral formations of the Carpathian-Balkan region: Moscow, Mingeo SSSR, 9 sheets, scale 1:1,000,000.

Cox, D.P., 1986, Model 17—Descriptive model of porphyry Cu, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 76.

Csontos, László, and Nagymarosy, András, 1998, The Mid-Hungarian Line; A zone of repeated tectonic inversions: Tectonophysics, v. 297, p. 51–71.

Csontos, L., Nagymarosy, A., Horváth, F., and Kovać, M., 1992, Tertiary evolution of the Intra-Carpathian area—A model: Tectonophysics, v. 208, p. 221–241.

De Saint Blanquat, Michel, Tikoff, Basil, Teyssier, Christian, and Vigneresse, Jean-Louis, 1998, Transpressional kinematics and magmatic arcs, *in* Holdsworth, R.E., Strachan, R.A., and Dewey, J.F., eds., Continental transpressional and transtensional tectonics: Geological Society Special Publication 135, p. 327–340.

Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, no. 6, p. 1123–1139.

Dimitrijević, M.D., 1974, The Dinarides; A model based on the new global tectonics, *in* Janković, Slobodan, ed., Metallogeny and concepts of the geotectonic development of Yugoslavia: Belgrade, University of Belgrade, p. 141–178.

Dimitrijević, M., and Grubić, A., 1977, Models of geotectonic development of the northeastern Mediterranean, *in* Janković, S., ed., Metallogeny and plate tectonics in the northeastern Mediterranean: International Conference on Metallogeny and Plate Tectonics in the Northeastern Mediterranean, Belgrade, December 7–9, 1976, Proceedings, p. 21–103.

Drew, L.J., 2003, Model of the porphyry copper and polymetallic vein family of deposits—Applications in Slovakia, Hungary, and Romania: International Geology Review, v. 45, no. 2, p. 143–156.

Drew, L.J., and Berger, B.R., 2001, Model of the porphyry copper/polymetallic vein kin-deposit system; Application in the Metaliferi Mountains, Romania, *in* Piestrzyński, Adam, ed., Mineral deposits at the beginning of the 21st century: Exton, Penn., A.A. Balkema Press, p. 519–522.

Drew, L.J., and Berger, B.R., 2002, Application of the porphyry copper/polymetallic vein kin deposit system to mineral-resource assessment in the Mátra Mountains, northern Hungary, *in* Fabbri, A.G., Gaál, Gabor, and McCammon, R.B., eds., Deposit and geoenvironmental models for resource exploitation and environmental security: Boston, Kluwer Academic Publishers, p. 171–186.

Drew, L.J., Berger, B.R., Bawiec, W.J., Sutphin, D.M., Csirik, Gÿorgy, Korpás, László, Vetö-Akos, Eva, Odor, László, and Kiss, János, 1999a, Mineral-resource assessment of the Mátra and Börzsöny-Visegrád Mountains, north Hungary: Geologica Hungarica, v. 24, p. 79–96.

Drew, L.J., Singer, D.A., Menzie, W.D., and Berger, B.R., 1999b, Mineral-resource assessment—State of the art: Geologica Hungarica, v. 24, p. 31–40.

Fodor, László, Csontos, László, Bada, Gábor, Györfi, István, and Benkovics, László, 1999, Tertiary tectonics evolution of the Pannonian Basin system and neighbouring orogens—A new synthesis of palaeostress data, *in* Durand, Bernard, Jolivet, Laurent, Horváth, Frank, and Séranne, Michel, eds., The Mediterranean Basins—Tertiary extension within the Alpine orogen: Geological Society Special Publication 156, p. 295–334.

Ghiţulescu, T.P., and Socolescu, M., 1941, Etude géologique et minière des Monts Métallifères: Anuarul Institutului Geologic al României, v. 21, p. 185–464.

Glazner, A.F., 1991, Plutonism, oblique subduction, and continental growth; An example from the Mesozoic of California: Geology, v. 19, no. 8, p. 784–786.

Grocott, John, Brown, Michael, Dallmeyer, R.D., Taylor, G.K., and Treloar, P.J., 1994, Mechanisms of continental growth in extensional arcs; An example from the Andean plate-boundary zone: Geology, v. 22, no. 5, p. 391–394.

Guilbert, J.M., and Park, Jr., C.F., 1986, The geology of ore deposits: New York, W.H. Freeman and Co., 985 p.

Harding, T.P., Vierbuchen, R.C., and Christie-Blick, Nicholas, 1985, Structural styles, plate-tectonic settings, and hydrocarbon traps of divergent (transtensional) wrench faults, *in* Biddle, K.T., and Christie-Blick, Nicholas, eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 51–77.

Hill, D.P., 1977, A model for earthquake swarms: Journal of Geophysical Research, v. 82, no. 8, p. 1347–1352.

Hollister, V.F., 1974, Regional characteristics of porphyry copper deposits of South America: Transactions of the Society of Mining Engineers, v. 255, p. 45–53.

Hollister, V.F., 1978, Geology of the porphyry copper deposits of the western hemisphere: New York, American Institute of Mining, Metallurgical and Petroleum Engineers, Society of Mining Engineers, 219 p.

Horváth, Ferenc, 1988, Neotectonic behavior of the Alpine-Mediterranean region, *in* Royden, L.H., and Horváth, Ferenc, eds., The Pannonian Basin—A study in basin evolution: American Association of Petroleum Geologists Memoir 45, p. 49–55.

Ivanov, Z., Georgiev, N., Lazarova, A., and, Dimov, D., 2002, New model of Upper Cretaceous magma emplacement in the southwestern parts of central Sredna Gora Zone, Bulgaria, *in* Michalík, Jozef, Simon, Ladislav, and Vozár, Jozef, eds., Proceedings of the XVII Congress of Carpathian-Balkan Geological Association, Bratislava, September 1–4, 2002, Guide to geological excursions: Geologica Carpathica, v. 53, special issue CD–ROM.

Janković, S., 1990, Types of copper deposits related to volcanic environment in the Bor district, Yugoslavia: Geologische Rundschau, v. 79, no. 2, p. 467–478.

Janković, S., Terzić, M., Aleksić, D., Karamata, S., Spasov, T., Jovanović, M., Miličić, M., Mišković, V., Grubić, A., and Antonijević, I., 1980, Metallogenic features of copper deposits in the volcano-intrusive complexes of the Bor district, Yugoslavia, *in* Janković, S., and Sillitoe, R.H., eds., European copper deposits; Proceedings of an International Symposium held at Bor, Yugoslavia, September 18–22, 1979: Belgrade, University of Belgrade, p. 42–49.

Janković, S., and Petkovic, M., 1982, Metallogeny of copper deposits in East Serbia, Mining in Yugoslavia, *in* Cuk, L., ed., Niro Privredni Vjesnik, Zagreb, p. 36–39.

Karamata, S., Knežević, V., Pécskay, Z., and Djordjević, 1997, Magmatism and metallogeny of the Ridanj-Krepoljin belt (eastern Serbia) and their correlation with northern and eastern analogues: Mineralium Deposita, v. 32, no. 5, p. 452–458.

Kouzmanov, Kalin, Bailly, Laurent, Ramboz, Claire, Rouer, Olivier, Bény, Jean-Michel, 2002, Morphology, origin and infrared microthermometry of fluid inclusions in pyrite from the Radka epithermal copper deposit, Srednogorie zone, Bulgaria: Mineralium Deposita, v. 37, no. 6/7, p. 599–613.

Kozelj, D.I., and Jelenkovic, R.J., 2001, Ore forming environments of epithermal gold mineralization in the Bor metallogenetic zone, Serbia, Yugoslavia, *in* Piestrzyński, Adam, ed., Mineral deposits at the beginning of the 21st century: Exton, Penn., A.A. Balkema Press, p. 535–538.

Lexa, J., Stohl, J., and Konečný, V., 1999, The Banská Stiavnica ore district; Relationship between metallogenetic processes and the geological evolution of a stratovolcano: Mineralium Deposita, v. 34, no. 5–6, p. 639–654.

Lindsay, D.D., Zentilli, Marcos, and Rojas de la Rivera, Jose, 1995, Evolution of an active ductile to brittle shear system controlling mineralization at the Chuquicamata porphyry copper deposit, northern Chile: International Geology Review, v. 37, no. 11, p. 945–958.

Maier, O., Nastaseanu, S., Potoceanu, E., and Stancu, Josefina, eds., 1973, Sasca: Institutul de Geologie şi Geofizică, no. 139a, sheet L–34–116–A, scale 1:50,000.

Malavieille, Jacques, 1993, Late orogenic extension in mountain belts; Insights from the Basin and Range and the late Paleozoic Variscan belt: Tectonics, v. 12, no. 5, p. 1115–1130.

Marsina, Karol, 1995, Evaluation of skarn related porphyry copper mineralization in the Stiavnické vrchy Mts. on the basis of lithogeochemical and some other criteria: Mineralia Slovaca, v. 27, p. 89–98.

Matenco, Liviu, and Schmid, Stefan, 1999, Exhumation of the Danubian nappes system (south Carpathians) during the Early Tertiary; Inferences from kinematic and paleostress analysis at the Getic/Danubian nappes contact: Tectonophysics, v. 314, no. 4, p. 401–422.

McKinstry, H.E., 1948, Mining geology: New York, Prentice-Hall, Inc., 680 p.

Milovanovic, B., 1968, Geologic map of the Kragujevac-Zaječar sheet: Institute of Geologic and geophysical research of Belgrade, Yugoslavia, 1 sheet, scale 1:200,000.

Nastaseanu, S., and Maier, O., eds., 1972, Moldova Nouă: Institutul Geologic, no. 139c, sheet L–34–116–C, scale 1:50,000.

Nastaseanu, S., Constantinof, D., Orasanu, Th., Stancu, Josefina, and Rogge-Taranu, Elena, eds., 1975, Oravita: Institutul de Geologie si Geofizica, no. 121c, sheet L–34–104–C, scale 1:50,000.

Neubauer, Franz, 2002, Contrasting Late Cretaceous with Neogene ore provinces in the Alpine-Balkan-Carpathian-Dinaride collision belt, *in* Blundell, D.J., Neubauer, F., and von Quadt, A., eds., The timing and location of major ore deposits in an evolving orogen: Geological Society Special Publication 204, p. 81–102.

Neubauer, Franz, Dallmeyer, R.D., Dunkl, Istvan, and Schirnik, Dieter, 1995, Late Cretaceous exhumation of the metamorphic Gleinalm dome, eastern Alps; Kinematics, cooling history and sedimentary response in a sinistral wrench corridor: Tectonophysics, v. 242, nos. 1–2, p. 79–98.

Norton, D.L., 1982, Fluid and heat transport phenomena typical of copper-bearing pluton environments, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, The University of Arizona Press, p. 59–72.

Oldow, J.S., Bally, A.W., and Avé Lallement, H.G., 1990, Transpression, orogenic float, and lithospheric balance: Geology, v. 18, no. 10, p. 991–994.

Park, R.G., 1983, Foundations of structural geology: London, Blackie & Son Limited, 135 p.

Parkinson, Christopher, and Dooley, Tim, 1996, Basin formation and strain partitioning along strike-slip fault zones: Bulletin of the Geological Survey of Japan, v. 47, no. 8, p. 427–436.

Peresson, Herwig, and Decker, Kurt, 1997, Far-field effects of late Miocene subduction in the Eastern Carpathians; E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region: Tectonics, v. 16, no. 1, p. 38–56.

Pollard, D.D., 1973, Derivation and evaluation of a mechanical model for sheet intrusions: Tectonophysics, v. 19, no. 3, p. 233–269.

Popov, P.N., 1987, Tectonics of the Banat-Srednogorie rift: Tectonophysics, v. 143, nos. 1–3, p. 209–216.

Popov, P., and Kovachev, 1996, Geology, composition and genesis of the ore mineralization in the central and southern Elatsite-Chelopech ore field, *in* Popov, P., ed., Plate tectonic aspects of the ore mineralization in the Carpatho-Balkan Region: Proceedings of the Annual Meeting UNESCO-IGCP Project No. 356, Sofia, 1996, v. 1, p. 159–170.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M., and Neugebauer, J., 1989, Extension in compressional orogenic belts; The eastern Alps: Geology, v. 17, no. 5, p. 404–407.

Ratschbacher, Lothar, Linzer, Hans-Gert, Moser, Franz, Strusievicz, Robert-Octavian, Bedelean, Horia, Har, Nicolae, and Mogoş, Petru-Adrian, 1993, Cretaceous to Miocene thrusting and wrenching along the central South Carpathians due to a corner effect during collision and orocline formation: Tectonics, v. 12, no. 4, p. 855–873.

Rogers, D.A., 1980, Analysis of pull-apart basin development produced by en echelon strike-slip faults, *in* Ballance, P.F., and Reading H.G., eds., Sedimentation in oblique-slip mobile zones: International Association of Sedimentologists Special Publication 4, p. 27–41.

Royden, Leigh, Horváth, Ferenc, and Rumpler, János, 1983, Evolution of the Pannonian Basin system—1. Tectonics: Tectonics, v. 2, no. 1, p. 63–90.

Rumpler, J., and Horváth, F., 1988, Some representative seismic reflection lines from the Pannonian basin and their structural interpretation, *in* Royden, L.H., and Horváth, Ferenc, eds., The Pannonian basin—A study in basin evolution: American Association of Petroleum Geologists Memoir 45, p. 153–169.

Schmid, S.M., Berza, Tudor, Diaconescu, Vlad, Froitzheim, Nikolaus, and Fügenschuh, Bernhard, 1998, Orogen-parallel extension in the Southern Carpathians: Tectonophysics, v. 297, p. 209–228.

Segall, P., and Pollard, D.D., 1980, Mechanics of discontinuous faults: Journal of Geophysical Research, v. 85, no. B8, p. 4337–4350.

Seraphim, R.H., and Hollister, V.F., 1976, Structural settings, *in* Brown, A.S., ed., Porphyry deposits of the Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 30–43.

Sibson, R.H., 1985, Stopping of earthquake ruptures at dilational fault jogs: Nature, v. 316, p. 248–251.

Sibson, R.H., 1986, Earthquakes and lineament infrastructure: Philosophical Transactions of the Royal Society of London, Series A, v. 317, p. 63–79.

Sibson, R.H., 1987, Earth rupturing as a mineralizing agent in hydrothermal systems: Geology, v. 15, no. 8, p. 701–704.

Sibson, R.H., 1989, Structure and mechanics of fault zones in relation to fault-hosted mineralization: Glenside, Southern Australia, Australian Mining Foundation, 66 p.

Singer, D.A., 1993, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, no. 2, p. 69–81.

Singer, D.A., Berger, V.I., and Moring, B.C., 2002, Porphyry copper deposits of the world; Database, maps, and preliminary analysis: U.S. Geological Survey Open-File Report 02–268, 61 p., 6 oversize sheets.

Sonder, L.J., and England, P.C., 1989, Effects of a temperature-dependent rheology on large-scale continental extension: Journal of Geophysical Research, v. 94, no. B6, p. 7603–7619.

Starostin, V.I., 1970, Bor and Majdanpek copper deposits in Yugoslavia: International Geology Review, v. 12, no. 4, p. 370–380.

Strashimirov, Strashimir, Petrunov, Rumen, and Kanazirski, Milko, 2002, Porphyry-copper mineralisation in the central Srednogorie zone, Bulgaria: Mineralium Deposita, v. 37, no. 6/7, p. 587–598.

Swanson, M.T., 1989, Structural duplexing in the strike-slip environment: U.S. Geological Survey Open-File Report 89–315, p. 376–385.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbold, P., 1982, Propagating extrusion tectonics in Asia; New insights from simple experiments with plasticine: Geology, v. 10, no. 12, p. 611–616.

Tapponnier, P., Peltzer, G., and Armijo, R., 1986, On the mechanics of the collision between India and Asia, *in* Coward, M.P., and Ries, A.C., eds., Collision tectonics: Geological Society Special Publication 19, p. 115–157.

Titley, S.R., 1990, Evolution and style of fracture permeability in intrusion-centered hydrothermal system, *in* The role of fluids in crustal processes: Studies in Geophysics, National Research Council, National Academy Press, Washington, p. 50–63.

Titley, S.R., and Beane, R.E., 1981, Porphyry copper deposits—Part I: Geologic settings, petrology, and tectogenesis: Economic Geology, 75th anniversary volume, p. 214–235.

Tosdal, R.M., and Richards, J.P., 2001, Magmatic and structural controls on the development of porphyry Cu±Mo±Au deposits, *in* Richards, J.P., and Tosdal, R.M., eds., Structural controls on ore genesis: Reviews in Economic Geology, v. 14, p. 157–181.

Willingshofer, E., 2000, Extension in collisional orogenic belts; Late Cretaceous evolution of the Alps and Carpathians: Ph.D. thesis, Netherlands Research School of Sedimentary Geology.

Willingshofer, E., Neubauer, F., and Cloetingh, S., 1999, The significance of Gosau-type basins for the Late Cretaceous tectonic history of the Alpine-Carpathian belt: Physics and Chemistry of the Earth, v. 24, no. 8, p. 687–695.

Yugoslavia Federal Geological Institute, 1970, SFR Yugoslavia, geological map— Institute of Geologic and geophysical research of Belgrade, Yugoslavia: Belgrade, Yugoslavia Institute for Geological and Mining Exploration and Investigation of Nuclear and Other Mineral Raw Materials, sheet 4, scale 1:500,000.

USGS

Lawrence J. Drew—**Tectonic Model for Spatial Occurrence of Porphyry Copper in Central Europe—Scientific Investigations Report 2005–5272**

ISBN 1-411-30960-X

9 781411 309609

Printed on recycled paper